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FUEL EFFECTS ON GAS TURBINE ENGINE COMBUSTION

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The objective of this study was to develop and/or improve correlations of fuel properties and engine design with combustion performance and hot section durability. The data base consisted primarily of fuel effect data obtained over the past four years under a number of DoD contracts.

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The approach taken was to first develop fuel effect correlations for specific combustor configurations, then to tie together these correlations using engine design parameters; thereby allowing prediction of fuel effects in any current or future aircraft gas turbine combustion system. In most cases statistical analysis was used to identify the correlating variables. The relationships developed for individual combustors were then correlated with combustor design and operating parameters that were influenced by fuel differences.

FOREWORD

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SYMBOLS

B	Mass transfer number
COP	Combustor operating parameter
c_p	Specific heat at constant pressure, cal/gK
D	Diameter, m
dq	Quenching distance
d_t	Droplet lifetime, s
E	Evaporation rate
f/a	Fuel-air ratio
FCP	Fuel characterization parameter
H	Heat of combustion
H_2	Hydrogen concentration, %
k	Fuel nozzle constant
L	Latent heat of vaporization
LSP	Liner severity parameter
M	Mass
m	Mass fraction
P	Pressure, kPa or MPa
ΔP	Pressure differential, kPa
PF	Combustor pattern factor
Pr	Prandtl number
Q	Heat content, cal/g
r^2	Coefficient of determination
r	Stoichiometric ratio
Re	Reynolds number
SLTO	Sea level take-off conditions
SMD	Sauter mean diameter, microns
T	Temperature, K
Tu	Turbulence intensity, % = 100 (u'/V)
u'	Root mean square of the fluctuating velocity, m/s
U	Velocity, m/s
V	Primary Zone Volume, m^3
VI	Vaporization index
W	Flow rate
z	Dropsize distribution factor
β	Sensitivity factor
δ	Specific gravity
η_c	Combustion efficiency
κ	Thermal conductivity
μ	Dynamic viscosity, kg/m-s
υ	Kinematic viscosity, m^2/s
ρ	Density, kg/m^3
σ	Surface tension, N/m
ϕ	Equivalence ratio

Subscripts

a	Air
d	Droplet
f	Fuel
g	Gas
i	Initial conditions
l	Liquid
L	Combustor liner
ox	oxygen
p	nozzle prefilmer lip
pri	Combustor primary zone
s	Droplet surface
v	fuel vapor
3	Combustor inlet
4	Combustor exit

SECTION I

SUMMARY

This study was undertaken with the objective of preparing a correlative model of the effect of fuel properties on the performance and life of United States Air Force gas turbine engine hot sections. The data base used in constructing the model consisted primarily of fuel effect data which has been obtained over the past few years under a number of Department of Defense contracts.

The approach taken in the study was to first develop fuel effect correlations for specific combustor configurations, then to tie together these correlations using engine design parameters, thereby allowing prediction of fuel effects in any current or future aircraft gas turbine combustion system. More specifically, the approach consisted of using statistical analysis to correlate the dominant fuel properties which affect combustor operation for individual combustors. The approach then consisted of cross correlating the individual combustor relationships against those combustor design and operating parameters that were found to influence their response to fuel differences.

All of the fuel relationships developed can be divided into two groups as follows:

- Those that are related to fuel vaporization and its effect on the rate the fuel ignites and burns
- Those tied to fuel chemistry and its effect on smoke generation and radiation.

Table 1 lists the fuel effects which have been correlated and the correlating parameters which were found to provide the best correlations. The first column in Table 1 lists the primary performance and operating factors which were evaluated. The second column lists the fuel related factors which were determined to influence individual combustors. The third column lists the specific correlations which were developed for the individual combustors studied, and the last column identifies the basis for generating the fuel effects to allow prediction of fuel related changes in performance and operation of any combustor.

TABLE 1. CORRELATION OF FUEL EFFECTS

Parameter Affected	*Governing Factor*	*Combustor Correlation Used*	*Basis for Generalized Correlation*
Altitude Relight	Spark quenching distance	Fuel Characteristic Parameter (FCP) Combustor Operating Parameter (COP)	Relative change in COP with FCP
Groundstart	Fuel vaporization	Vaporization Index (VI)	Priiary zone operating conditions
Combustion Efficiency	Fuel vaporization	Vaporization Index (VI)	Combustion efficiency correlation parameter (Ref. 15)
Pattern Factor	Fuel vaporization	Vaporization Index (VI)	Relative sensitivity
Smoke and Particulates	Fuel composition	Hydrogen Content	Relative sensitivity
Liner Temperature (Radiation)	Fuel composition	Hydrogen Content	Relative sensitivity

The fuel characteristic parameter and combustor operating parameter used to predict altitude relight performance were developed from Ballal and Lefebvre's equation for ignition of heterogeneous mixtures in a flowing stream (Reference 7). The vaporization index was developed as a relative measure of the tendency of the fuel spray to vaporize. It was selected over several other atomization-related parameters which were evaluated and contains fuel property terms which account for relative drop size, relative heat transfer to the droplet and relative volatility of the fuel.

Smoke and radiation-related parameters were found to correlate well with hydrogen content. The effect of fuel atomization and naphthalene concentration on smoke formation were also evaluated. It appeared that atomization might have a secondary effect at some conditions; but, the effect was too small relative to the data scatter to obtain a correlation. Somewhat surprisingly, naphthalene was also shown to have no greater effect on smoke than would be predicted from the change produced in hydrogen concentration. Naphthalene concentration did appear to have a secondary effect on ignition, but this effect was also too small relative to the data scatter to correlate.

A number of approaches to generalizing the individual combustor relationships were evaluated. Generally, correlation of fuel effects against combustor operating parameters was not very successful. In most cases, the best correlations were empirical correlations of the sensitivity of the performance effect to fuel property variations, against the value of the performance parameter with some reference fuel (usually JP-4). For example, the sensitivity of smoke number to hydrogen content for most combustors correlates very well with the value of the smoke number with JP-4. Pattern factor and combustion efficiency show similar trends, but a more complete combustion efficiency correlation was obtained using Odgen and Carrier's correlation parameter (Reference 15). An exception to the general trend was the groundstart correlation which was based on primary-zone equivalence ratio and primary-zone entrance conditions.

In most cases, reasonably good data correlations have been obtained. Examination of the correlations provides good insight into the nature and extent of the effect of fuel property variations on engine performance and operation. There is reason to believe that much of the data scatter found in the correlations is due more to inaccuracies in the basic data than to errors or incompleteness in the correlations. Further improvements in the correlations will require (1) improved instrumentation, (2) testing over an even wider range of fuel properties (particularly viscosity and hydrogen content) than previous testing, and (3) fuel effects testing in specially instrumented complete engine systems.

SECTION II

INTRODUCTION

Over the past decade the cost of petroleum-based fuels has risen dramatically. Fuel availability is no longer dependable, as illustrated by the petroleum shortages of 1973 and 1979. During the same period, the increasing use of highly aromatic crude oil has resulted in a deterioration of jet fuel quality. To offset these problems, increasing consideration is being given to broadening specifications to reduce the cost and improve the availability of both the petroleum-based fuels in use today and the shale- and tar sands-derived fuels of the future.

A number of experimental evaluations to determine the effect of potential fuel changes on aircraft engine performance and operability have been sponsored by the Air Force and Navy over the past few years. These studies have provided a wealth of data for the particular engines and engine components which have been tested. The objective of the "Fuel Effects on Gas Turbine Engine Combustion" study has been to use this data base to develop correlations of fuel effects on combustor performance and hot section durability and to relate these correlations to engine design parameters so that these parameters may be universally applied to any current or future aircraft gas turbine combustion system. Together, the correlations developed constitute a model which will be used to:

- Conduct trade-off studies of engine performance and life with fuel cost and availability.

- Guide preparation of new or modified fuel specifications.

- Provide rapid evaluation of a deviate fuel in emergency situations.

- Reduce, and, in some cases eventually eliminate, the time and cost of qualifying a new fuel.

- Act as a design tool for new or modified combustion systems to better accommodate future fuels.

The "Fuel Effects on Gas Turbine Engine Combustion" program had been originally planned to consist of two Tasks. Task I was to consist of developing quantitative relationships between combustor operating characteristics and fuel properties and developing a comprehensive plan for combining the relationships into a generalized working model. This report presents the results of the Task I effort. Task II, which has not been undertaken, was to consist of completing the generalization of the relationships obtained in Task I and organizing them into a cohesive package which may be programmed as a computer model of existing combustors, and used as a design tool for future combustors.

The development of the Task I relationships was conducted in two steps: (1) determination of fuel sensitivity correlations for individual combustors and (2) correlation of the fuel affected combustor design and operating parameters to obtain a generalized fuel effect model which may be applied to any conventional combustor. Relationships were developed for:

- Altitude ignition limits
- Groundstart ignition capability
- Combustion efficiency
- Pattern factor

- Smoke
- Peak combustor wall temperature.

The fuel sensitivity study was accomplished by correlating the preceding performance characteristics with parameters based on fuel properties reflecting known or suspected combustion trends. The correlations were based primarily on statistical analyses of fuel effects data from references 1 through 5. Statistical analyses were used to (1) compare various correlation parameters to select the most appropriate one, (2) show the validity of the selected correlation and (3) provide an expression of fuel sensitivity which could be used in the development of the generalized fuel effect model. The fuel sensitivity model is described in detail in Section III.

The generalized fuel effect model consists of correlations of the sensitivity of the fuel effect to variations in some basic combustor design or operating parameter, e.g., the air loading parameter (θ), (Reference 6). Separate correlations were developed for each of the performance relationships listed above. The development of the model is discussed in Section IV.

The fuel effect correlations developed under Task I have been based entirely on data taken from experimental combustor component test data, rather than full-scale engine tests. Experience has shown that there may be significant performance shifts between component and full-scale engine data. While the fuel effect correlations developed in Task I are believed to accurately reflect fuel trends, they must be anchored to baseline engine data to predict engine performance. The computer model planned for Task II was to have provisions for anchoring the fuel effect relationships to baseline engine data.

SECTION III

FUEL EFFECTS CORRELATIONS

A. FUEL PROPERTY CORRELATION APPROACH

The development of fuel correlations for specific combustors is described in this section. Correlations were developed for altitude ignition, groundstart, combustion efficiency, pattern factor, smoke, and peak combustor wall temperature. The correlation approach taken was to utilize regression analyses to select the fuel property parameter which produced the best statistical result. Generally, the correlation equations were in the form:

$$Y = A_o + A_1X_1$$

where:

- Y represents the observed engine parameter (e.g., smoke, groundstart fuel-air ratio, pattern factor),
- X represents the fuel properties correlation parameter,
- A represents the sensitivity of the observed engine parameter to variation of the fuel properties correlation parameter.

Note that X is a fuel correlation parameter that may consist of one or many fuel-related variables; for example, fuel viscosity, fuel density, fuel hydrogen content or a combined parameter which combines several fuel properties which relate to the physical processes involved.

For determination of the most applicable correlating parameter, two methods were used. In some cases the correlation was expanded to include a second term. The equation then takes the form:

$$Y = A_o + A_1X_1 + A_2X_2.$$

Comparison of the degree of correlation with the expanded equation to the original equation indicated the desirability of including the additional term. In other cases, a number of single variable relationships were developed and compared on the basis of the correlation coefficients. In all cases, a single variable relationship was selected as being the most applicable.

B. ALTITUDE IGNITION LIMITS

For some engines, altitude ignition appears to be the single most significant combustor performance variable affected by fuel property variations. A model was developed to correlate the effect of fuel properties on altitude relight performance using rig data from the F100, TF33, TF30, F101 and J79 combustors. The model is based on an ignition equation formulated by Ballal and Lefebvre (Reference 7) and was originally developed for the TF30 combustor under an NAPC sponsored contract (Reference 8).

The ignition model is based on the assumption that mixing rates and chemical kinetics are infinitely fast and that the sole criterion for successful ignition is an adequate concentration of fuel vapor in the ignition zone, i.e., the process is independent of chemical reaction kinetics and is evaporation controlled. It is assumed that the igniter discharge creates a region of inflamed gas that must grow to a minimum volume to sustain combustion and propagate throughout the combustor. The growth of the inflamed region is determined by conflicting processes of fuel vapor production and external heat loss. Thus, the model provides a criteria for ignition based on quenching distance in terms of mass transfer number, the initial fuel droplet diameter, and aerothermal parameters which depend on combustor operating conditions.

For turbulent flowing mixtures:

$$dq = \frac{0.32\, Pr_a\, \rho_f}{Z\phi \ln(1+B)} \left[\frac{(SMD)^3 (Tu/100)\, U}{\rho_a\, \mu_a}\right]^{0.5} \qquad \text{(Reference 7) (1)}$$

Where:
- dq = Quenching distance
- Pr_a = Prandtl number (air)
- ρ_f = Density (fuel) kg/m^3
- SMD = Sauter mean diameter (microns)
- Tu = Percentage turbulence intensity = 100 (u'/U)
- u' = Root-mean-square value of the fluctuating velocity m/s
- U = Free stream air velocity m/s
- Z = Drop size distribution factor (considered to be constant)
- ϕ = Equivalence ratio
- B = Mass transfer number (stoichiometric)
- μ_a = Dynamic viscosity (air) $kg/m \cdot s$

Based on this equation, the ignition model was formulated by eliminating all constants and explicitly combining fuel properties into a single parameter referred to as the fuel characterization parameter (FCP).

$$FCP = \frac{\rho_f (SMD)^{1.5}}{\ln(1+B)} \qquad (2)$$

The aerothermal combustor parameters, which vary with altitude and Mach number, were similarly grouped together in a term referred to as the combustor operating parameter (COP).

$$COP = \frac{Pr_a (Tu/100)^{.5}\, U^{.5}}{\rho_a^{.5}\, \mu_a^{.5}\, \phi} \qquad (3)$$

By use of these terms, the variation in atomization quality from one nozzle design to another is removed. The impact of the fuel type is expressed through the process of evaporating mass transfer. Following the convention of Spalding (Reference 9), the rate of evaporative mass transfer is related to the fuel droplet diameter and mass transfer number which is the ratio of the energy available for vaporization to the energy required. This mass transfer number is given by:

$$B = \frac{m_{ox} H/r + c_p (T_g - T_s)}{Q} \tag{4}$$

Where:
- m_{ox} = Fractional mass concentration of oxygen
- H = Heat of combustion (cal/g)
- r = Stoichiometric ratio
- c_p = Specific heat at constant pressure (cal/g·K)
- T_g = Combustor inlet temperature (K)
- T_s = Initial boiling point temperature (K)
- Q = Heat conducted from gas per unit mass crossing the phase boundary (cal/g)

  $Q = L_s + c_{pl} (T_s - T_o) = L_o + c_{pv} (T_s - T_o)$

- L_s = Latent heat of vaporization at the droplet surface temperature (cal/g)
- c_{pl} = Specific heat of the liquid (cal/g·K)
- T_o = Initial liquid temperature
- c_{pv} = Specific heat of the vapor.
- L_o = Latent heat of vaporization at temperature T_o

1. Pressure Atomizing Nozzles

To calculate the FCP for a particular combustor, the fuel spray droplet Sauter mean diameter (SMD) must be determined for the particular combustion system of interest. The TF30 and TF33 combustor systems employ pressure atomizing fuel nozzles. An empirical correlation parameter for this type atomizer (Reference 10) was used to estimate the fuel spray droplet diameter, i.e.:

$$SMD = k W_f^{.25} \upsilon_f^{.20} \sigma_f^{.60} \Delta P_f^{-.40} \tag{5}$$

where:
- k = constant (dependent on fuel nozzle design)
- W_f = Fuel flow (kg/s)
- υ_f = Kinematic viscosity (m^2/s)
- σ_f = Surface tension (N/m)
- ΔP_f = Pressure drop in the fuel nozzle passage

From equation (1), separating the terms dependent on combustor aerodynamics from those which are dependent only on fuel physical properties, the following mathematical expressions for FCP and COP are obtained:

$$FCP = \frac{\rho_f \upsilon_f^{.3} \sigma_f^{.9}}{\ln (1+B)} \tag{6}$$

$$COP = \frac{Pr_a (Tu/100)^{.5} U^{.5} W_f^{.375}}{\rho_a^{.5} \mu_a^{.5} \phi \Delta P_f^{.6}} \tag{7}$$

2. Airblast Nozzles

The F100 and F101 engines employ airblast atomizing fuel nozzles. Shanawany and Lefebvre's correlation parameter for this type of atomizer (Reference 11) was used to estimate the relative fuel spray droplet diameter.

$$\mathrm{SMD} = \left[1 + \frac{W_f}{W_a}\right]\left[0.073 \left(\frac{\sigma_f}{\rho_a U^2}\right)^{.6} \left(\frac{\rho_f}{\rho_a}\right)^{.1} D_p^{.4} + .015 \left(\frac{\mu_f^2 D_p}{\sigma_f \rho_f}\right)^{.5}\right] \tag{8}$$

where: D_p = Prefilmer lip diameter (m)
W_a = Air flowrate (kg/s).

Since the second term in equation (8) is relatively small, in comparison to the first term, and the product of the air density times the square of the air free stream velocity is directly proportional to the pressure drop across the fuel nozzle system, equation (8) becomes

$$\mathrm{SMD} = 0.073 \quad (\sigma_f^{.6} \rho_f^{.1} \Delta P_a^{-.6} \rho_a^{-.1} D_p^{.4}) \left(1 + \frac{W_f}{W_a}\right) \tag{9}$$

Separating the terms dependent on combustor aerodynamics from those which are dependent only on fuel physical properties and eliminating the constants, (including D_p) the following mathematical expressions for airblast nozzles are obtained:

$$\mathrm{FCP} = \frac{\rho_f^{1.15} \sigma_f^{.9}}{\ln (1+B)} \tag{10}$$

$$\mathrm{COP} = \frac{Pr_a (Tu/100)^{.5} U^{.5} (1 + W_f/W_a)^{1.6}}{\rho_a^{.65} \mu_a^{.5} \phi \Delta P_a^{.9}} \tag{11}$$

3. Combustor Altitude Ignition Correlations

Fuel physical properties and ignition data from TF30, TF33, F100, F101 and J79-17C engines were used to generate a fixed relationship between COP and FCP, as shown in Figures 1, 3, 5, 7, and 8, respectively.* For the TF30, TF33 and F100 engines, the COP is calculated from the windmilling conditions as defined on the windmill map. The map relates flight Mach number and altitude to compressor discharge conditions. The relationship between COP and altitude for the TF30, TF33 and F100 is shown in Figures 2, 4 and 6, respectively. The values of COP for the F101 and J79 engines were calculated directly from the altitude relight test results (Reference 2 and 3).

The data generally show a linear relationship between COP and FCP. There is some data scatter, particularly with the F100 engine at maximum and minimum airflows. Nevertheless, the expected trend towards decreasing ignition capability with increasing FCP was evident. Combustor systems which employ airblast rather than pressure atomizing fuel nozzles tend to be less sensitive to changes in fuel properties as indicated by the low slopes of the F100 and F101 COP vs FCP curve. Note that the absolute values of COP and FCP are functions of combustor design parameters which vary substantially from engine-to-engine. Consequently, direct comparison of FCP and COP values is meaningless and one must instead compare the effect of relative changes in FCP on the altitude ignition limit.

* Because of the large number of figures appearing in this section, all figures have been placed at the end of the section.

C. GROUNDSTART, COMBUSTION EFFICIENCY, PATTERN FACTOR AND LEAN BLOWOUT

The processes affecting groundstart, combustion efficiency and burner temperature uniformity (pattern factor) are primarily fuel spray atomization and evaporation. The processes are influenced by the size of the droplets formed by the spray nozzle, the heat transferred to the fuel droplet, and the volatility of the fuel. The correlating parameters for groundstart, combustion efficiency and pattern factor were selected to evaluate the relative importance of droplet size and vaporization rate. From a comparison of these parameters, the one which best correlated the fuel data for all of the engines considered was selected.

The correlative parameters used in the data analysis included fuel recovery temperature, relative droplet size, the Spalding mass transfer number and several expressions which combined droplet size and mass transfer number. Analysis of the evaporation of a single droplet would suggest that the droplet lifetime is proportional to the square of the droplet diameter divided by a function of the mass transfer number, i.e.,

$$d_t \propto \frac{\rho_f D^2}{\ln(1 + B)} \tag{12}$$

This relationship follows from simplifying and eliminating fuel-independent terms from the following equations:

$$M_D = \frac{\pi}{6}\rho_f D^3$$

$$E_f = 2\pi D \frac{\kappa_a}{c_{p_a}} \ln(1+B)(1 + 0.25Re_D^{.5}) \qquad \text{(Reference 7)}$$

where:
M_D = Droplet mass (kg)
D = Droplet diameter (microns)
E_f = Fuel evaporation rate (kg/s)
Re_D = Droplet Reynolds number
κ_a = Air thermal conductivity (J/m·s·K)

then the droplet lifetime, d_t is:

$$d_t = \frac{M_D}{E_f} = \frac{(\pi/6)(\rho_f)D^3}{2\pi D(\kappa/c_p)_a \ln(1+B)(1 + 0.25Re_D^{0.5})}$$

Equation (12) is based on a single droplet. The average lifetime for an array of droplets would be proportional to this expression (using SMD for D) if the number of droplets remained constant as SMD changed and the relative size distribution remained unchanged. Based on these assumptions, an expression termed the vaporization index (VI) was defined:

$$VI = \frac{\delta(SMD/SMD_{ref})^2}{\ln(1+B)} \tag{13}$$

where δ is the fuel specific gravity and the subscript "ref" indicates a reference value based on JP-4. The fuel property variations are thus included in the equations which define the average droplet diameter and the mass transfer number. The appropriate operational characteristics of the fuel nozzle are also included in the droplet diameter term.

Two additional correlation expressions were evaluated to explore changing the relative importance of SMD and B, i.e.,

$$VI_1 = \frac{\delta(SMD/SMD_{ref})}{\ln(1+B)} \tag{14}$$

$$VI_3 = \frac{\delta(SMD/SMD_{ref})^3}{\ln(1+B)}. \tag{15}$$

A complete list of correlating parameters is given in Table 2.

TABLE 2. FUEL PROPERTIES AND CORRELATING PARAMETERS

10% Recovery Temperature (RT)
90% Recovery Temperature (RT)
Mass Transfer Number (B) (Based on 10% or 90% Recovery Temperature)
Relative Spray Droplet Size
Vaporization Index (VI) (Based on 10% or 90% Recovery Temperature) (Relative SMD term to the first, second, or third power)

Correlations were compared for the F100, TF33, TF30, F101, J79-17C and TF41 engines. A computer program entitled Statistical Applications for Engineers (SAFE) was used to generate correlation coefficients for each correlating parameter. The correlating parameters were defined as the independent variables in a single-variable linear regression analysis. They are used to relate fuel property changes to changes in groundstart fuel-air ratio, efficiency, and pattern factor, the dependent variables in the regression analysis. These regression analysis results were then examined for cause/effect relationships. A good correlation was judged to be one which would indicate a significant cause/effect relation with a coefficient of determination (r^2) of more than 0.40. This is a somewhat arbitrary number, however, and is strongly influenced by the range of fuel properties upon which the data are based. For example, the larger the range of SMD and B in the VI correlation, the greater the r^2 for a given instrumentation error.

The correlation results from the ground start, combustion efficiency and pattern factor analysis are shown in Tables 3, 4 and 5. Groundstart results are shown for three different air flows for the F100, TF33 and TF30 engines, but data for only one airflow were available for the other engines. Combustion efficiency was only correlated at the idle power point as efficiency losses at other power points were generally too low to measure.

TABLE 3. GROUNDSTART DATA CORRELATIONS (SINGLE VARIABLE LINEAR REGRESSION SUMMARY COEFFICIENT OF DETERMINATION r^2)

Correlation Parameter	*F100****	*TF33****	*TF30****	*F101*	*J79-17C***	*TF41***
10% Recovery	0.5658/(0.9213)*	0.0561	—	—	—	—
Temperature	0.0919/(0.8538)	0.2954				
	0.0061/(0.3434)	0.3327				
Relative Spray Droplet	0.9878	0.4510	0.6047	0.2563	0.9172/0.7773	0.4062/0.2825
	0.6422/(0.9090)	0.8468	0.8405			
	0.4309/(0.5323)	0.8030	0.9855			
Mass Trans. Number	0.5677/(0.9421)	0.0912	0.3453	0.1649	0.7687/0.8111	0.3101/0.1720
(10% RT)	0.0970/(0.9230)	0.2644	0.6973			
	0.0136/(0.4656)	0.3333	0.7255			
Vaporization Index	0.8605/(0.9503)	0.2733/(0.9454)	0.6025	0.2471	0.9417/0.6614	0.4533/0.2799
10% RT	0.3753/(0.8897)	0.6874	0.8489			
$(SMD_f/SMD_{JP_4})^3$	0.1844/(0.4622)	0.6534	0.9799			
Vaporization Index	0.8209	0.2672/(0.9696)	0.5985	0.2514	0.9395/0.7260	0.3457/0.2654
10% RT	0.3290/(0.8950)	0.6433	0.8535			
$(SMD_f/SMD_{JP_4})^2$	0.1527/(0.4723)	0.6283	0.9835			
Vaporization Index		0.1336/(0.8668)				
10% RT		0.4298				
$(SMD_f/SMD_{JP_4})^1$		0.4487				

Note * (   ) Indicates one point was eliminated to improve the correlation
**Data shown for standard day/cold day
***Values are given at three different air flows.

Selection of the most desirable correlating parameter from those evaluated is not obvious. All of the correlating parameters achieve some degree of correlation for some variables and some engines, and none of them do a good job in all cases. Selection of the optimum correlation is confused by:

- An apparent high degree of data scatter in some cases

- The inherent interrelationship of fuel viscosity and vapor pressure which makes separation of droplet size and volatility effects difficult.

In general, it can be seen from Tables 3, 4, and 5 that the best correlations were most consistently achieved using the parameter which included both relative droplet size and mass transfer number, i.e., vaporization index. Vaporization index using droplet size to the 2.0 power was selected on the basis of having the best basis in theory since there was no clear-cut numerical advantage over the other two VI parameters.

TABLE 4. COMBUSTION EFFICIENCY AT IDLE (SINGLE VARIABLE LINEAR REGRESSION SUMMARY COEFFICIENT OF DETERMINATION r^2)

Correlation Parameter	*F100*	*TF33*	*TF30*	*F101*	*J79-17C*	*TF41*
90% Recovery, Temperature (RT)	0.9216	0.0895/(0.6574)*	0.0795/(0.0987)	0.0411	0.0662	0.0563
Relative Spray Droplet	0.6356	0.5059/(0.7295)	0.1025/(0.3077)	0.7273	0.1449	0.0818
Mass Trans. Number	0.9261	0.3472	0.1041/(0.1253)	0.1760	0.0866	0.0062
Vaporization Index 90% RT $(SMD_f/SMD_{JP4})^3$	0.7748	0.5822/(0.8275)	0.0982/(0.2744)	0.6767	0.1345	0.1006
Vaporization Index 90% RT $(SMD_f/SMD_{JP4})^2$	0.8291	0.5557/(0.8154)	0.1008	0.6691	0.1480	0.0946
Vaporization Index 10% RT $(SMD_f/SMD_{JP4})^1$	0.8939	0.5144/(0.7966)	0.1032			

Note* ( ) indicates one point was eliminated to improve correlation.

TABLE 5. PATTERN FACTOR AT SLTO (SINGLE VARIABLE LINEAR REGRESSION SUMMARY COEFFICIENT OF DETERMINATION r^2)

Correlation Parameter	*F100*	*TF33*	*TF30*	*F101*	*J79-17C*	*TF41*
90% Recovery, Temperature (RT)	0.5976/(0.7103)*	0.7766	0.3908	0.2920	0.0398	0.0967
Relative Spray Droplet	0.3985/(0.9416)	0.1558	0.0338	0.5193	0.0145	0.1117
Mass Trans. Number 90% RT	0.6000/(0.7451)	0.7234	0.0757	0.3230	0.0160	0.1306
Vaporization Index 90% RT $(SMD_f/SMD_{JP4})^3$	0.4143/(0.9351)	0.2214	0.0476	0.4506	0.0061	0.1354
Vaporization Index 90% RT $(SMD_f/SMD_{JP4})^2$	0.4650/(0.9290)	0.2158	0.0502	0.5018	0.0101	0.1334
Vaporization Index 10% RT $(SMD_f/SMD_{JP4})^1$	0.5232/(0.9023)	0.3046	0.0562	0.4425		

Note * ( ) Indicates one point was eliminated to improve the correlation.

Gas turbine fuels are complex mixtures of many hydrocarbon compounds. Their volatility is generally expressed in terms of the fraction of the fuel which can be distilled at a given temperature. Frequently, when a single temperature is needed to describe the relative volatility of the fuel, the 50% distillation temperature is used. In combustion, however, the lighter fuel fractions within the fuel tend to influence ignition (particularly under lean conditions), while the heavier fractions would be expected to have more influence on pattern factor and combustion efficiency. To determine if the selection of the distillation fraction had a significant effect on the accuracy of the vaporization index (VI) correlation, both the 10% and 90% distillation temperatures were used to compute the VI for correlation of combustion efficiency. The results are compared in Table 6. The 90% temperature showed an improved correlation over the 10% temperature for the F100, but a poorer agreement with the F101. In other cases, the differences were insignificant. The lack of a clear-cut distinction is blamed on data scatter and the inherent relationship between the 10% and 90% distillation temperatures in most fuels. For lack of a clear numerical difference, the 10% distillation temperature was selected for use in the VI for correlation of ignition data, and the 90% distillation temperature was selected for VI correlations of combustion efficiency and pattern factor.

TABLE 6. COMBUSTION EFFICIENCY CORRELATION AT IDLE COEFFICIENT OF DETERMINATION r^2

Combustors	*Vaporization Index 10% Recovery Temp.*	*Vaporization Index 90% Recovery Temp.*
F100	0.5831	0.7748
TF33	0.6060	0.5822
TF30	0.0587	0.0982
F101	0.7413	0.6767
J79	0.1452	0.1345
TF41	0.1116	0.1006

Plots illustrating groundstart, combustion efficiency and pattern factor correlations are shown in Figures 9 through 26. The dotted lines in these curves represent the 95% confidence band. For any value of the correlation parameter, e.g. VI, the interval about the Y axis between the dotted lines represents the true value of Y with 95% confidence.

A good correlation was obtained for the groundstart fuel air ratio as a function of VI. The larger value of VI indicates a reduced tendency to vaporize, and as a result, a larger total fuel flow rate is required to generate the same level of fuel vapor. The data from idle combustion efficiency show a high degree of correlation, with efficiency decreasing slightly with an increased VI. The VI is an increasing function of fuel viscosity and a decreasing function of fuel volatility. Pattern factor data also show a good degree of correlation. While the degree of change in pattern factor is small, the potential impact on turbine life is significant.

Changes in the combustor lean blowout limits would be expected to be correlateable with fuel droplet size and volatility. Fuel flammability limits would also affect lean blowout, but no significant fuel differences would be expected and flammability limit data were not available for the various test fuels.

An excellent correlation of lean blowout limit with VI was obtained using J79-17C groundstart lean blowout data (Figure 27). Unfortunately data for the other engines studied either showed no significant fuel effect or excessive data scatter when correlated with VI, e.g., see Figure 28. Assessment of the blowout data for specific combustors may be summarized as follows:

- J79-17C — Good correlation of groundstart data indicates significant fuel effect. Excessive data scatter in altitude blowout data.

- J79-17A — Excessive data scatter in both groundstart and altitude lean blowout.

- F100 — No groundstart blowout data. Altitude blowout data show excessive data scatter.

- F101 — Groundstart and altitude data both show considerable data scatter and blowout values are suspiciously high. Fuel effect on groundstart is small.

- TF33 — No groundstart data. Altitude data show considerable scatter.

- TF41 — Fuel effect is small. Lack of fuel temperature data prevents calculation of VI.

- TF30 — Limited data indicates small effect.

Because so few correlations of blowout were formulated for specific combustors, no attempt was made to correlate fuel effects with engine design variables.

D. SMOKE AND RADIATION

Whereas most of the combustor operating parameters affected by the fuel may be related to fuel physical properties, smoke and flame radiation have generally been linked to changes in fuel chemistry. Under some conditions, fuel physical property variations may also affect smoke and radiation, but these conditions appear to be primarily at low power operating points where smoke and the effect of radiation on combustor life are not of significant concern. The impact of fuel physical properties on smoke formation was investigated to a limited extent, but failing to find a quantitative correlation, only chemical effects were considered in the radiation correlations.

1. Smoke

Carbon particles are commonly formed in the primary zones of gas turbine combustors. To some extent, these particles are consumed in the lean combustion zone downstream of the primary zone. Depending on the rate of formation and growth and the extent of subsequent oxidation, some fraction of these particles are emitted from the combustor. Particles, whose diameter is approximately equivalent to the wavelength of visible light or smaller, will follow the streamlines of the flow through the turbine and will be exhausted from the engine as smoke. Larger particles may impinge on the turbine blades and vanes, eroding the surface, and contributing to reduced turbine life.

The influence of the fuel on the formation of smoke may be exerted through both the fuel chemistry and those physical properties which influence fuel-air mixture preparation. Some studies have shown that hydrogen content alone provides a valid basis for correlating chemical effects, while other studies have indicated that the presence of multicyclic compounds such as naphthalenes, indans and tetralins cause smoke in excess of their effect on reduced hydrogen content. The approach taken in this study was first to correlate the cumulative effect of changes in hydrogen content and relative droplet size with only those fuels that had relatively low total concentrations of naphthalenes, indans and tetralins (less than 10% by volume) and then to repeat the correlations including the fuels which contained higher concentrations of these constituents for comparison.

The correlations were generated using the Statistical Applications for Engineers (SAFE) computer program and involved a multi-variable linear equation of the following form:

$$y = c + a_i x_i \ldots a_n x_n, \text{ for } i = 1,2 \ldots n \tag{16}$$

where: x_i = fuel properties
a_i = coefficient of x_i term
n = total number of correlating parameters.

Comparison of the correlation coefficients for correlations with and without fuels containing high concentrations of naphthalenes, indans and tetralins is summarized in Table 7. Had the multicyclic compounds shown a consistent significant increase in smoke, correlations including these fuels would have shown an appreciable reduction in the correlation coefficients. It can be seen, however, that there is actually little change; indicating that on the average, the fuels containing multicyclic components generate approximately the same amount of smoke at any given hydrogen content.

TABLE 7. COEFFICIENTS OF DETERMINATION FOR SMOKE NUMBER AS A FUNCTION OF RELATIVE HYDROGEN CONTENT AND DROPLET SIZE AT CRUISE POWER LEVEL

Engines	*Fuels With Naphthalene Plus Indans and Tetralin Less Than 10% By Wt.*	*All Fuels*
F100	0.9195	0.9504
TF33	0.7332	0.7967
F101	0.6330	0.7115
J79	0.9285	0.9019
TF41	0.2272	0.2614

Correlations were also developed to statistically evaluate the importance of fuel properties on smoke formation. Physical property effects were evaluated through inclusion of relative drop size with hydrogen content in the smoke correlations. Coefficients of determination (r^2) and term coefficients (a_i) for smoke number versus an optimized correlation of hydrogen content and relative drop size are compared in Tables 8 and 9. All of the r^2 values are above 0.50. indicating good correlation. However, comparison of term coefficient for relative drop size and hydrogen content generally indicates a weaker dependence of smoke number on droplet size than on hydrogen content.

TABLE 8. COEFFICIENTS OF DETERMINATION FOR SMOKE NUMBER AS A FUNCTION OF RELATIVE HYDROGEN CONTENT AND DROPLET SIZE

Power Levels	*F100*	*TF33*	*F101*	*J79*	*TF41*
Cruise 1	0.9504	0.7967	0.7145	0.9019	0.2614
Cruise 2	—	0.8966	—	—	—
SLTO	0.6132	0.7800	0.5159	0.4591	0.5455
Dash	0.3783	—	0.5552	0.5552	0.2638

TABLE 9. TERM COEFFICIENTS FOR RELATIVE HYDROGEN CONTENT AND DROPLET SIZE

	F100			*TF33*			*F101*			*J79-17C*			*TF41*		
Parameter	*Cruise*	*SLTO*	*Dash*	*Cruise*	*Cruise 2*	*SLTO*	*Cruise*	*SLTO*	*Dash*	*Cruise*	*SLTO*	*Dash*	*Cruise*	*SLTO*	*Dash*
Relative Droplet Size	1.0323	−1.9401	0.7019	−2.0638	0.4269	0.8163	0.7319	0.7074	0.8503	2.4224	0.2378	−0.3266	−0.1542	−0.0163	−0.0192
Relative Hydrogen Content	−1.3352	−2.9015	−0.3983	−9.0857	−4.0188	−0.7039	−2.3663	−1.4114	−1.2443	−8.217	−3.5631	−4.1518	−2.6522	−1.4709	−1.0663

The SAFE program was also used to identify those parameters in the regression analysis which were statistically significant in correlating smoke number. In Table 10, the T-value indicates the relative statistical significance and the $T_{(.95,N)}$ is a reference minimum value for clear statistical significance.

It can be seen that in all but two out of fifteen cases where hydrogen content and relative droplet size are considered together, the T-value is higher for hydrogen content than for relative drop size and in only one of fifteen cases is the T-value for relative drop size higher than $T_{(.95,N)}$.

$$\text{where T}-\text{value} = \left(\frac{\text{Correlation Coefficient}}{\text{Err}}\right)_i \quad i = 1,\ldots n \tag{17}$$

$T_{(.95,\,N)}$ = Students t distribution at 95 percentile and number of data points.

Furthermore, in general, the correlation coefficient was somewhat improved when droplet size was removed from the correlation.

In some cases, it appears that the droplet size dependence, while small, may be real. In other cases, the droplet size correlation does not even follow expected trends (negative a_i). While it is concluded that droplet size may in some cases have a second order effect on smoke, there was insufficient data to reliably quantify the effects.

One recent report has suggested that smoke point might provide a better correlation of smoke than hydrogen content (Reference 13). The average correlation coefficient for 17 cases for correlation of smoke point with smoke number was 0.531, while the average correlation coefficient for hydrogen content with smoke number was 0.535 for the same 17 cases. Both are acceptable with insignificant differences. The close agreement between the two correlations is probably due to the inherent correlation of hydrogen content with smoke point as shown in Figure 29.

The final correlations of hydrogen content with smoke number for all of the cases studied are shown in Figures 30 through 35.

TABLE 10. ANALYSIS OF THE STATISTICAL SIGNIFICANCE OF RELATIVE DROPLET SIZE AND HYDROGEN CONTENT ON SMOKE NUMBER

	F100						*TF33*					
	Cruise		*SLTO*		*Dash*		*Cruise*		*Cruise 2*		*SLTO*	
	T-Value	$T_{(0.95, N)}$	*T-Value*	$T_{(0.95, N)}$	*T-Value*	$T_{(0.95, N)}$	*T-Value*	$T_{(0.95, N)}$	*T-Value*	$T_{(0.95, N)}$	*T-Value*	$T_{(0.95, N)}$
Relative Droplet T-RDS	1.22		0.71		0.35		0.61		0.29		0.93	
Size and Hydrogen		3.17		3.17		3.17		3.17		3.17		3.17
Content Combined T-H_2	2.34		1.58		0.29		2.12		2.13		0.64	
Relative Hydrogen Content	7.06	2.77	2.20	2.77			2.98	2.77	5.8	2.77		
Relative Droplet Size					1.50	2.77					3.46	2.77

	F101						*J79-17C*					
	Cruise		*SLTO*		*Dash*		*Cruise*		*SLTO*		*Dash*	
	T-Value	$T_{(0.95, N)}$	*T-Value*	$T_{(0.95, N)}$	*T-Value*	$T_{(0.95, N)}$	*T-Value*	$T_{(0.95, N)}$	*T-Value*	$T_{(0.95, N)}$	*T-Value*	$T_{(0.95, N)}$
Relative Droplet T-RDS	1.76		1.62		2.09		5.42		0.47		0.59	
Size and Hydrogen		2.23		2.23		2.23		2.20		2.20		2.20
Content T-H_2	3.93		2.23		2.11		7.75		2.94		3.17	
Relative Hydrogen Content	4.25	2.20	2.64	2.20	2.49	2.20	4.62	2.18	3.12	2.18	3.21	2.18

Criteria: If T-Value $\geq T_{(0.95\ N)}$ indicates parameter in regression model statistically significant and parameter with the lowest T-Value Was Removed

	TF41					
	Cruise		*SLTO*		*Dash*	
	T-Value	$T_{(0.95, N)}$	T-Value	$T_{(0.95, N)}$	T-Value	$T_{(0.95, N)}$
Relative Droplet T-RDS	0.16		0.06		0.05	
Size and Hydrogen		2.26		2.26		2.26
Content T-H_2	1.78		3.28		1.78	
Relative Hydrogen Content	1.87	2.28	3.46	2.23	1.89	2.23

2. Solid Particulates

In general, the availability of particulate data is more limited than smoke data; however, there is an inherent correlation between the two. Figure 36 illustrates TF33, F100 and TF30-measured particulate levels versus smoke number. The figure also shows a correlation between smoke number and particulates taken from Reference 14. Reference 14 gives an upper and lower bound for the correlation and the solid line shown is an average between the two. Smoke should correlate perfectly with particulate concentration if (1) average particle size remains constant or changes linearly with smoke number, and (2) the particle size distribution remains constant. It can be seen that the two measurements correlate reasonably well. The data scatter is probably due more to the accuracy of the relatively difficult measurement than in errors due to the correlation.

3. Radiation and Combustor Liner Temperature

Any changes in the combustor process which results in a change in the heat transfer to the combustor liner will affect combustor life. Any effect of fuel property variations on the combustion process and the resultant liner temperatures is, therefore, of primary concern.

While the convective heat load from the combustion process has not been found to change significantly, changes in fuel chemistry (hydrogen content) have been found to affect combustion by producing a more luminous flame and hence a higher radiative heat load. The impact of hydrogen content on the combustion process and the sensitivity of the liner metal temperature to radiative heat transfer were determined by normalizing the liner metal temperature rise to the gas temperature rise. Both temperature rises are referenced to the compressor discharge temperature. The normalized temperature ratio is defined analytically as:

$$\text{Liner Severity Parameter (LSP)} = \frac{T_{L(max)} - T_3}{T_4 - T_3} \tag{18}$$

where: T_3 = Compressor discharge temperature
$T_{L(max)}$ = Maximum liner temperature
T_4 = Combustor exit temperature.

Correlations of Liner Severity Parameter (LSP) versus hydrogen content were generated for the F100, TF33, TF30, F101, J79 and TF41, as shown in Figures 37 through 42. A good correlation was obtained for the LSP as a function of hydrogen content. The trend toward increased radiation with decreasing hydrogen content is evident for all of the combustors studied.

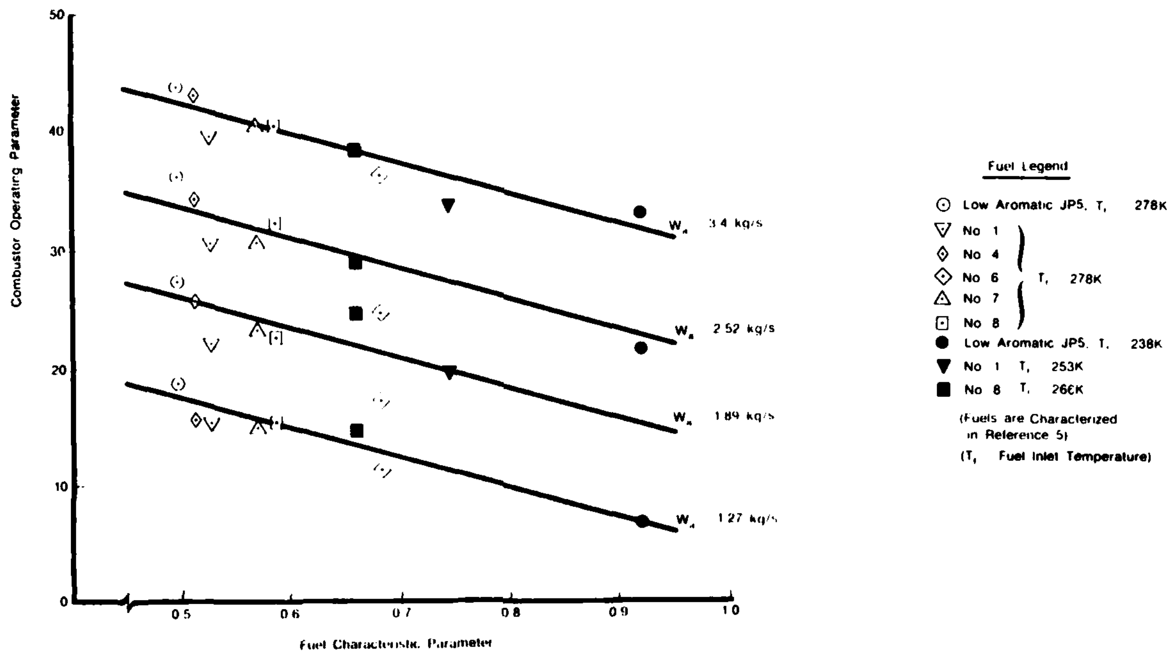


Figure 1. Relationship of TF30 Combustor Operating Parameter to Fuel Characteristic Parameter

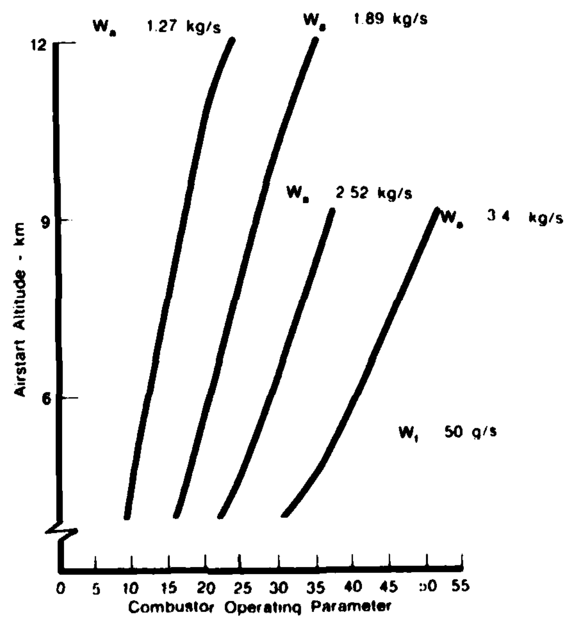


Figure 2. Effect of Combustor Operating Parameter on TF30 Relight Altitude

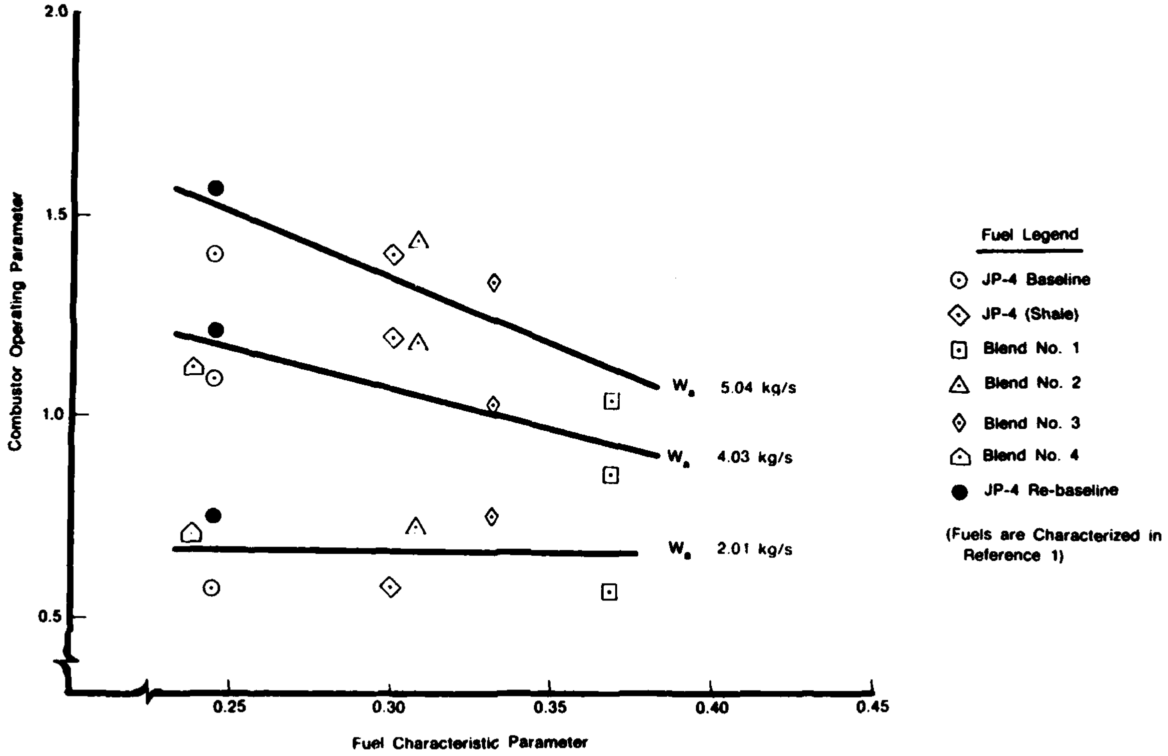


Figure 3. Relationship of TF33 Combustor Operating Parameter to Fuel Characterization Parameters

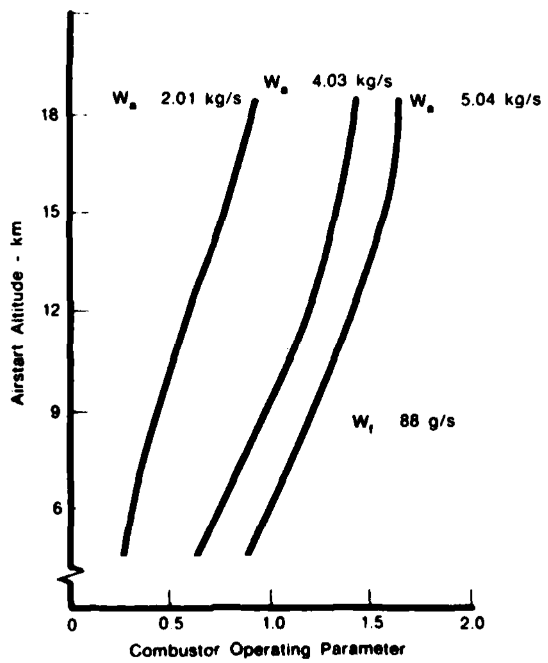


Figure 4. Effect of Combustor Operating Parameter on TF33 Relight Altitude

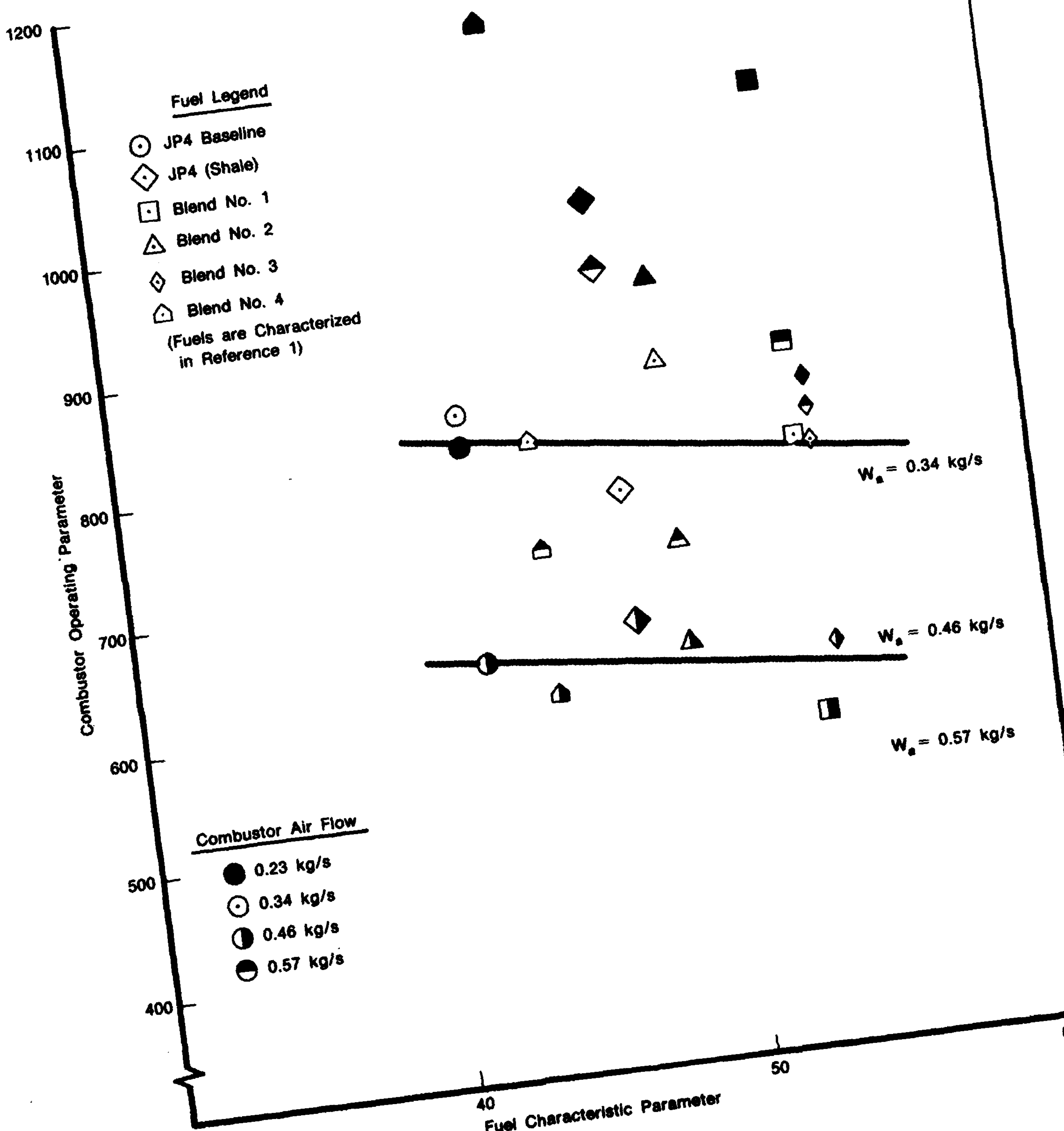


Figure 5. Relationship of F100 Combustor Operating Parameter to Fuel Characteristic Parameter

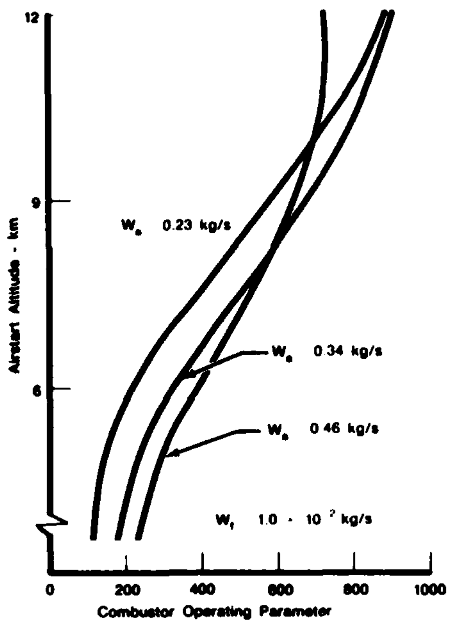


Figure 6a. Effect of Combustor Operating Parameter on F100 Altitude Relight

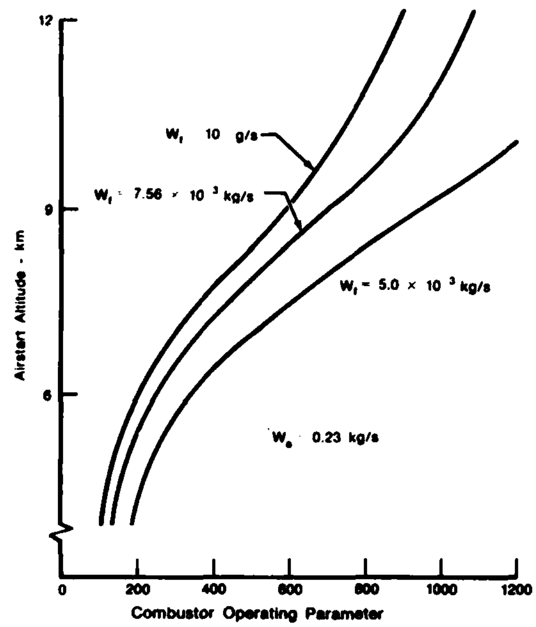


Figure 6b. Effect of Combustor Operating Parameter on F100 Altitude Relight

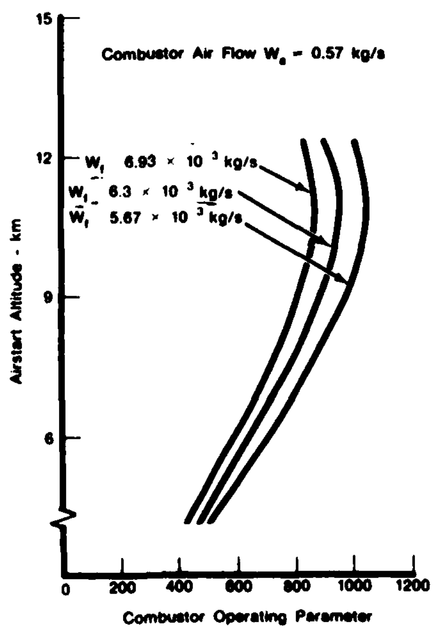


Figure 6c. Effect of Combustor Operating Parameter on F100 Altitude Relight

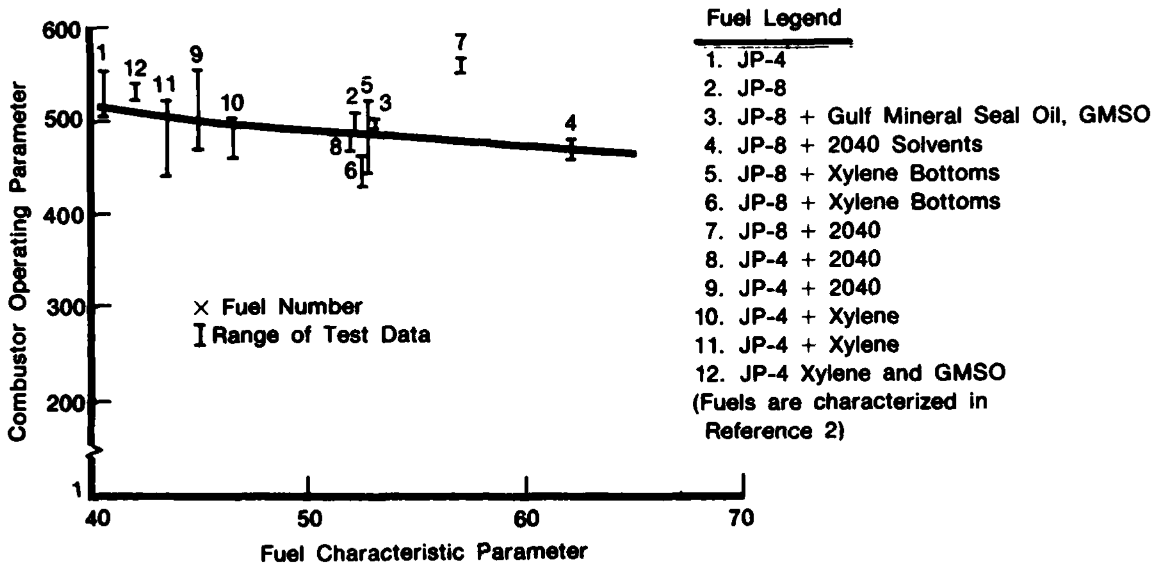


Figure 7. Relationship of Combustor Operating Parameter to Fuel Characteristic Parameter — F101

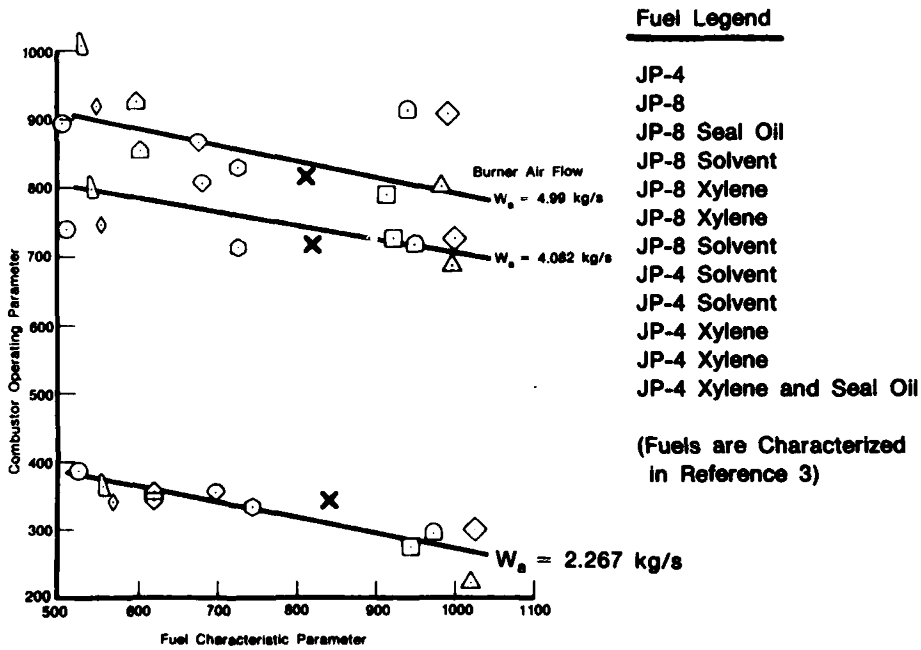


Figure 8. Relationship of Combustor Operating Parameter to Fuel Characteristic Parameter — J79-17C

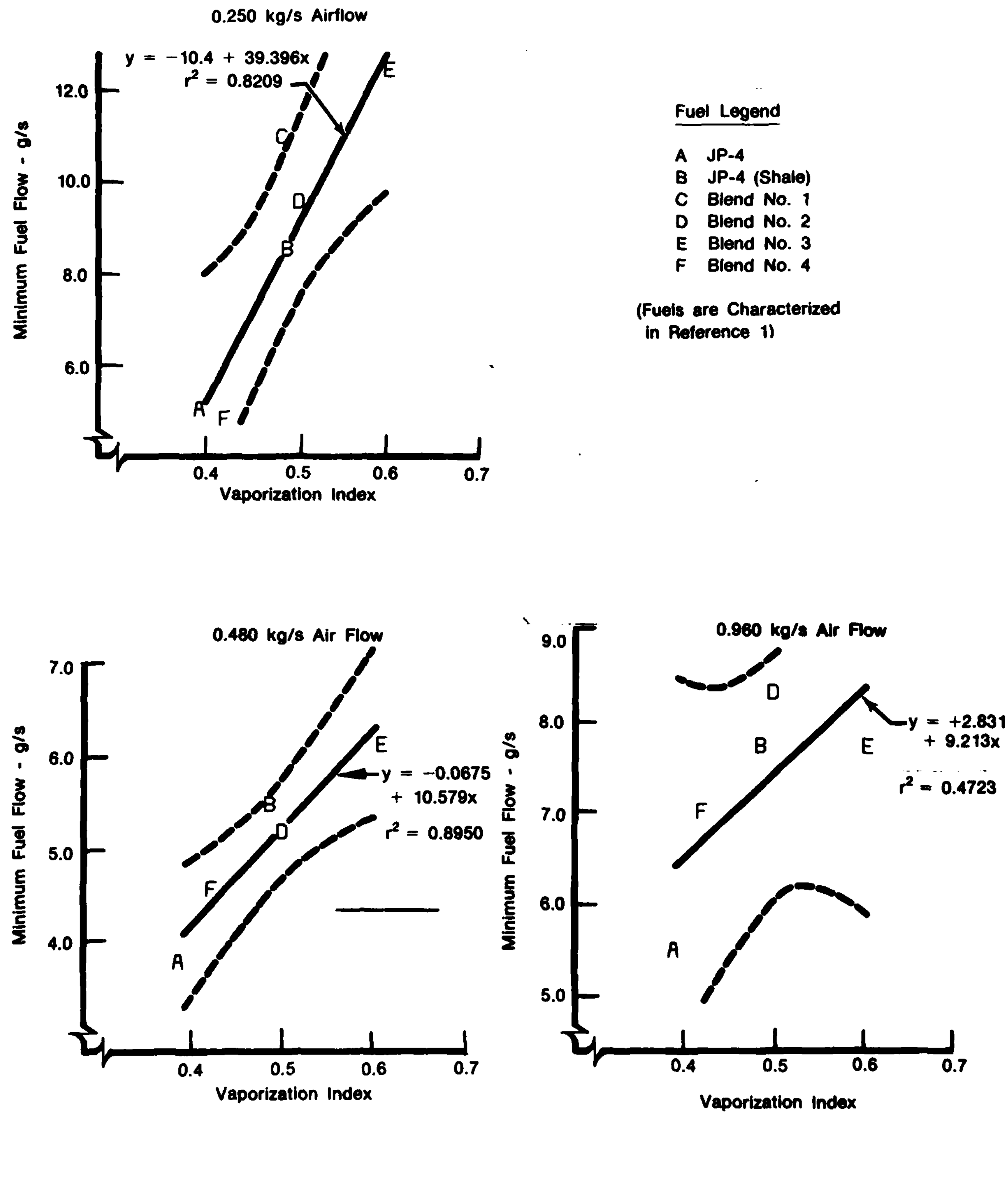


Figure 9. F100 Groundstart Data Correlation

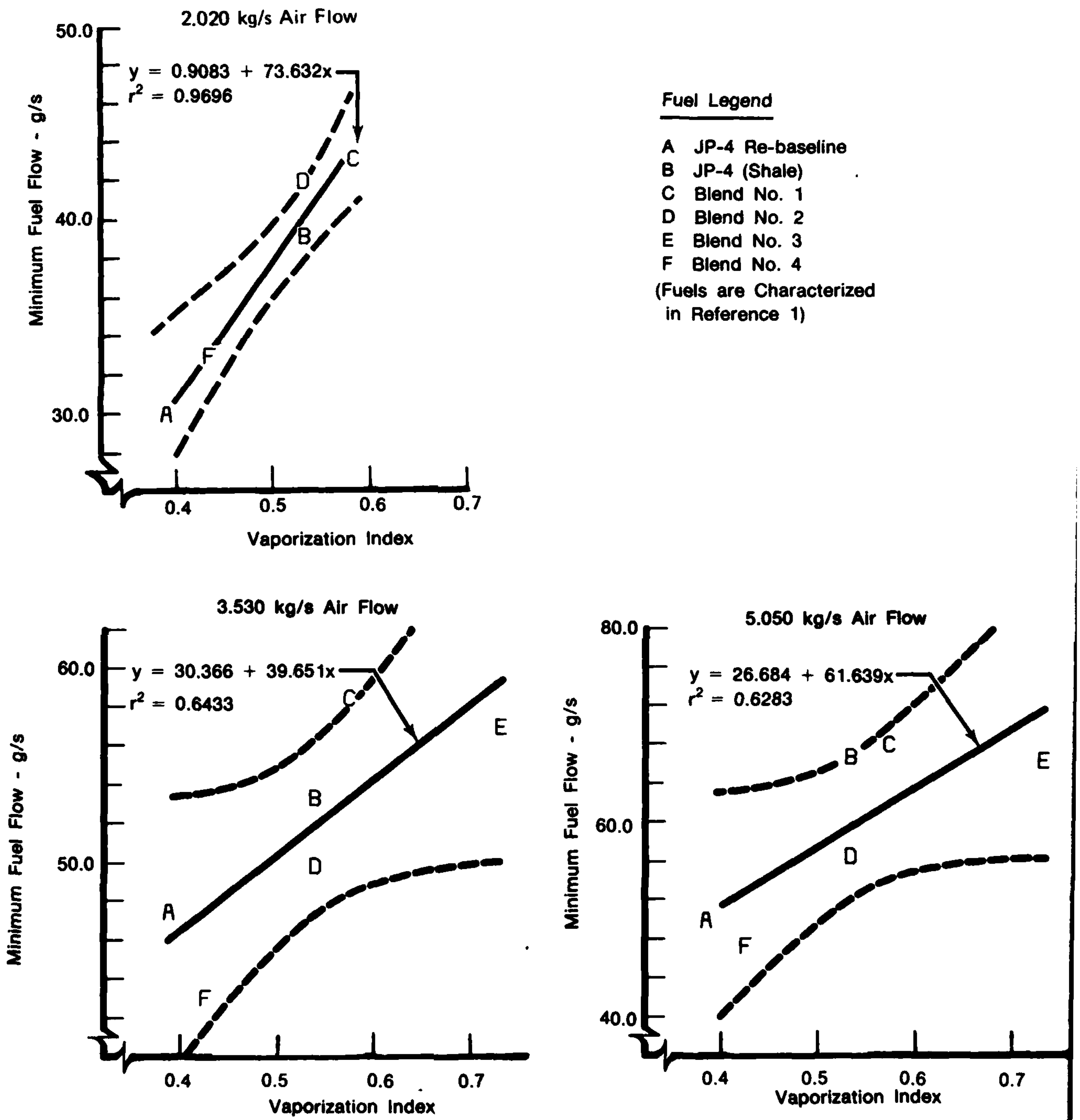


Figure 10. TF33 Groundstart Data Correlation

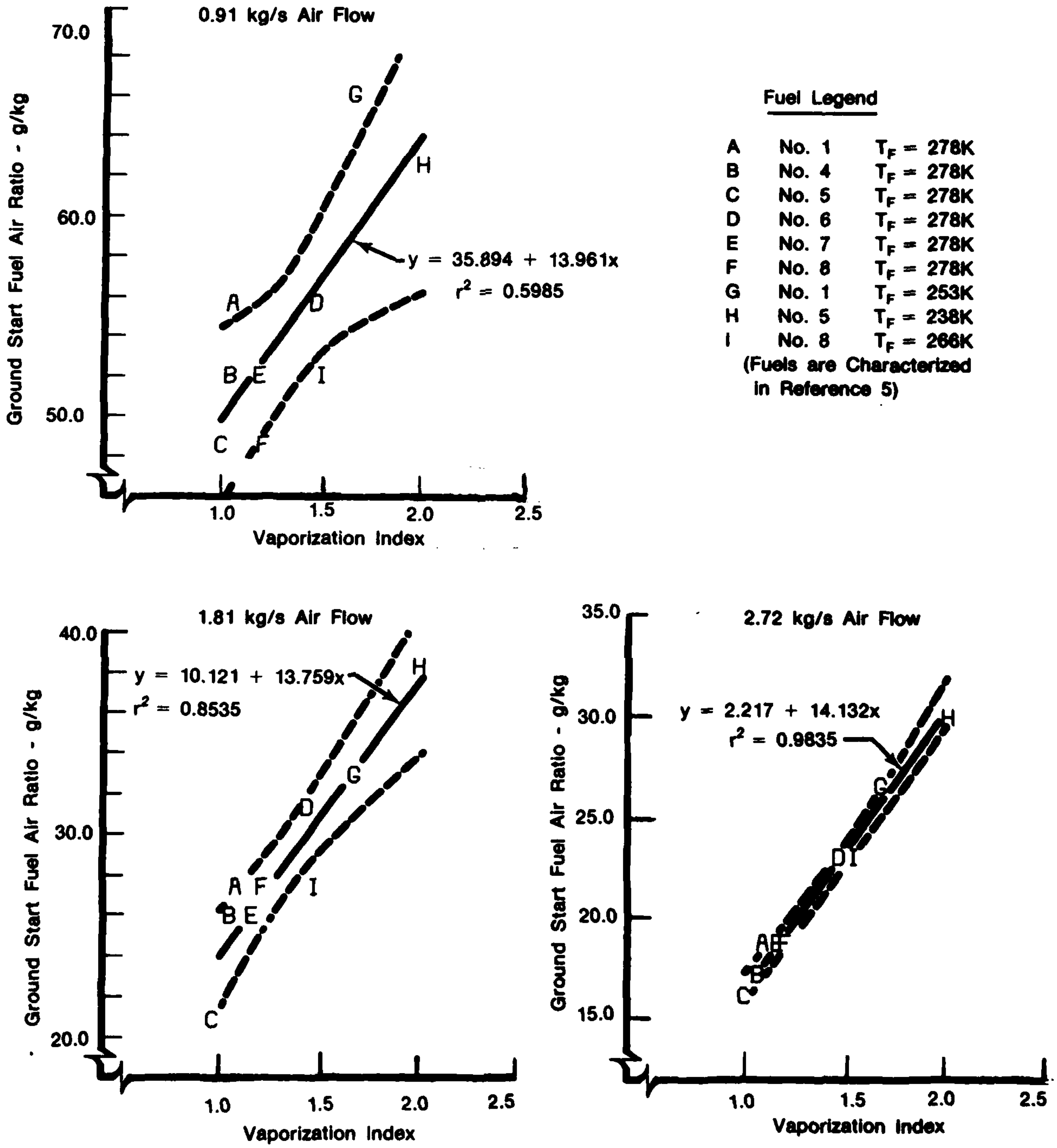


Figure 11. TF30 Groundstart Data Correlation

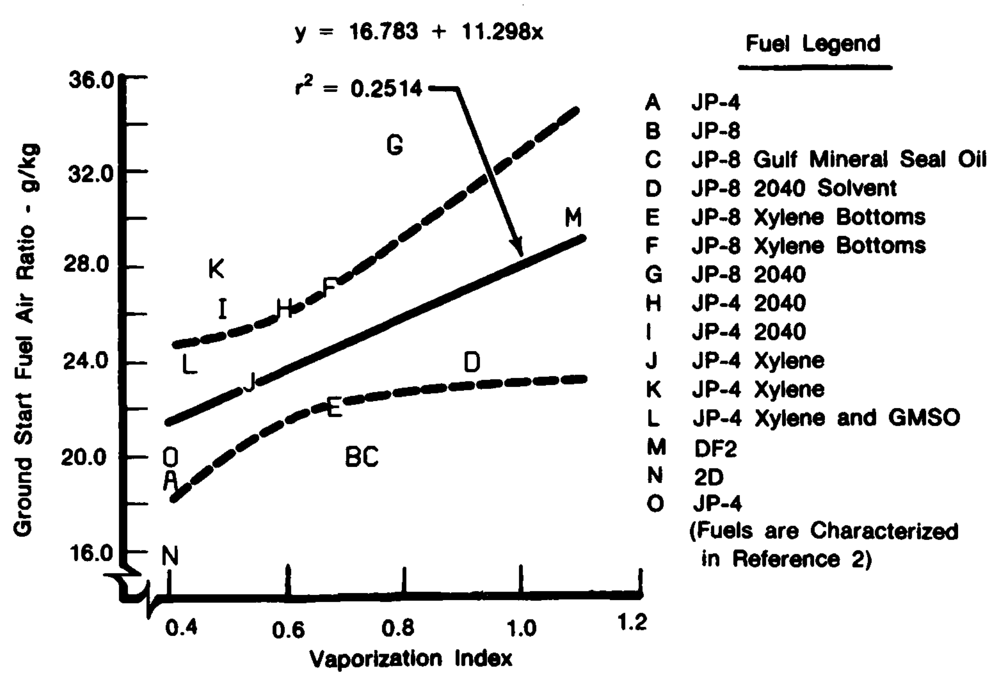


Figure 12. F101 Groundstart Data Correlation (1.15 kg/s Air Flow)

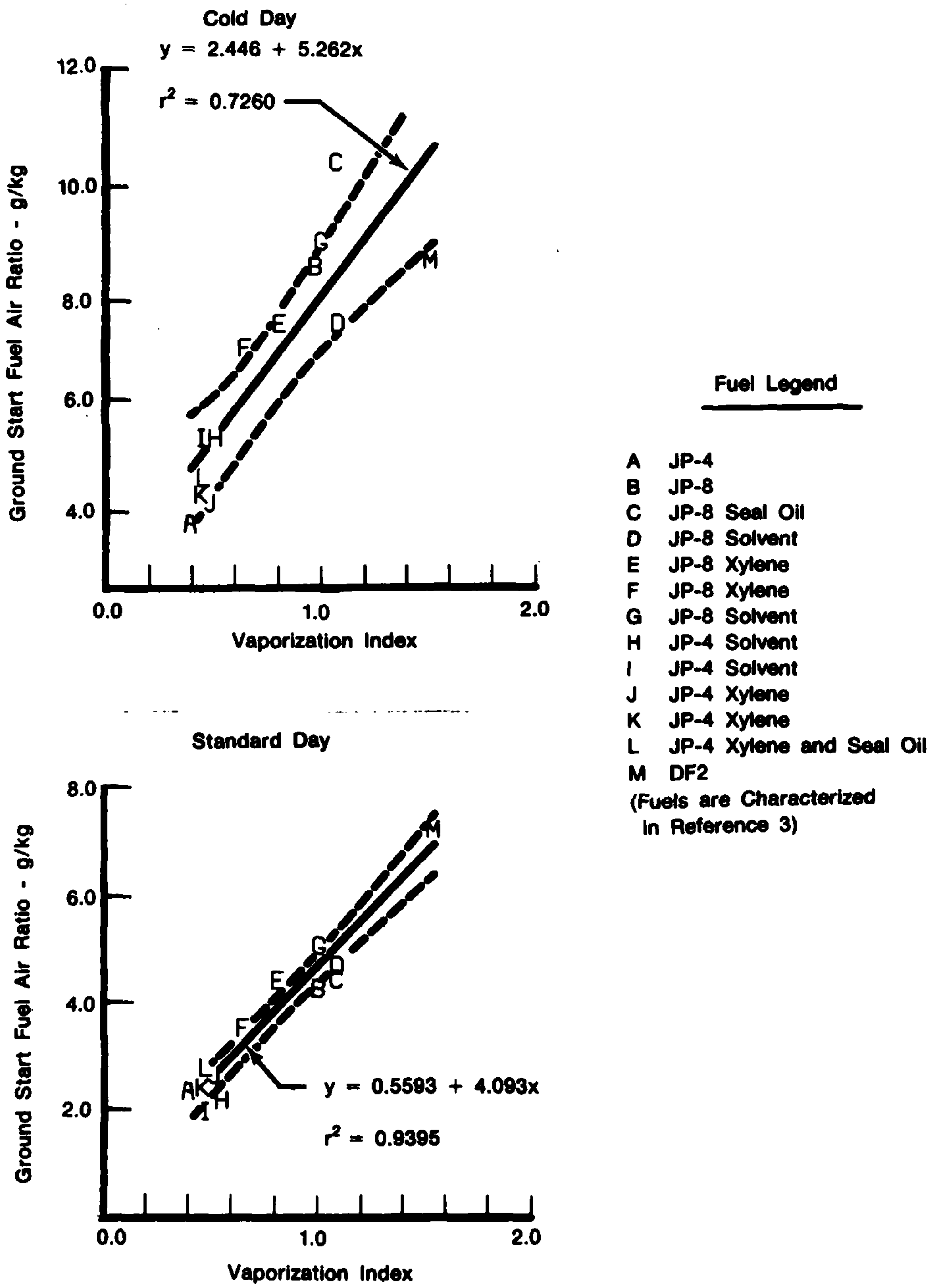


Figure 13. J79-17C Groundstart Data Correlation (3.18 kg/s Air Flow)

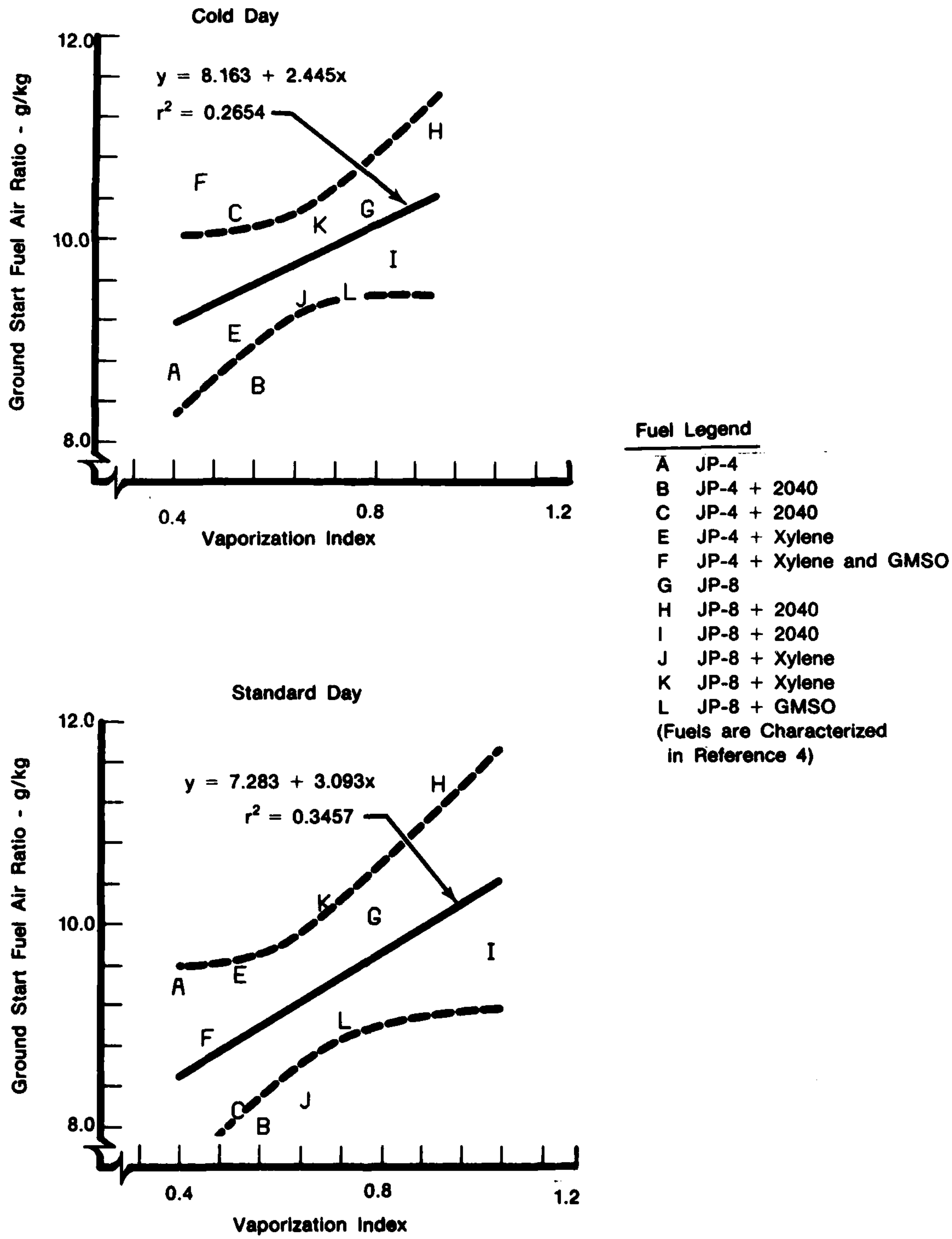


Figure 14. TF41 Groundstart Data Correlation (0.79 kg/s Air Flow)

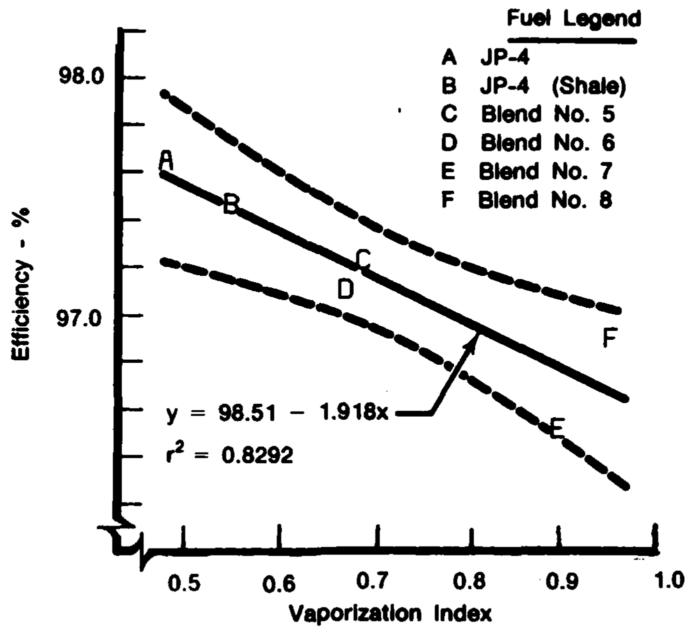


Figure 15. F100 Combustion Efficiency at Idle

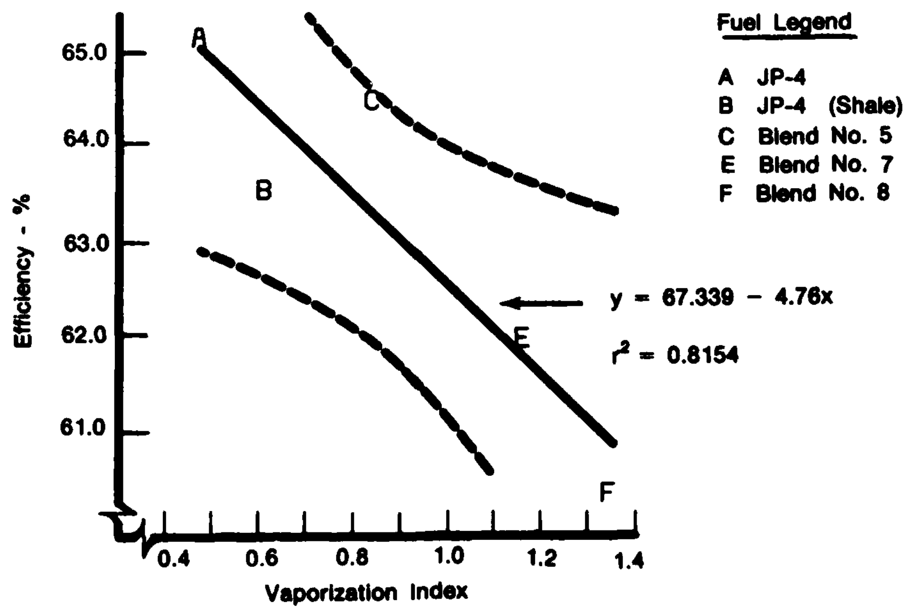


Figure 16. TF33 Combustion Efficiency at Idle

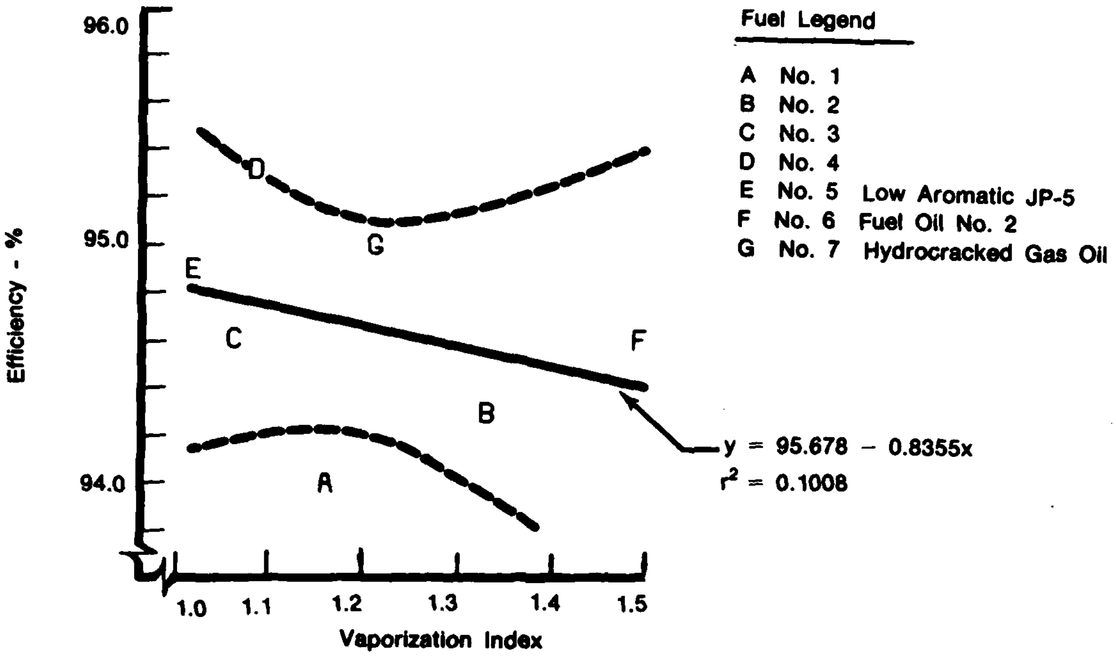


Figure 17. TF30 Combustion Efficiency at Idle

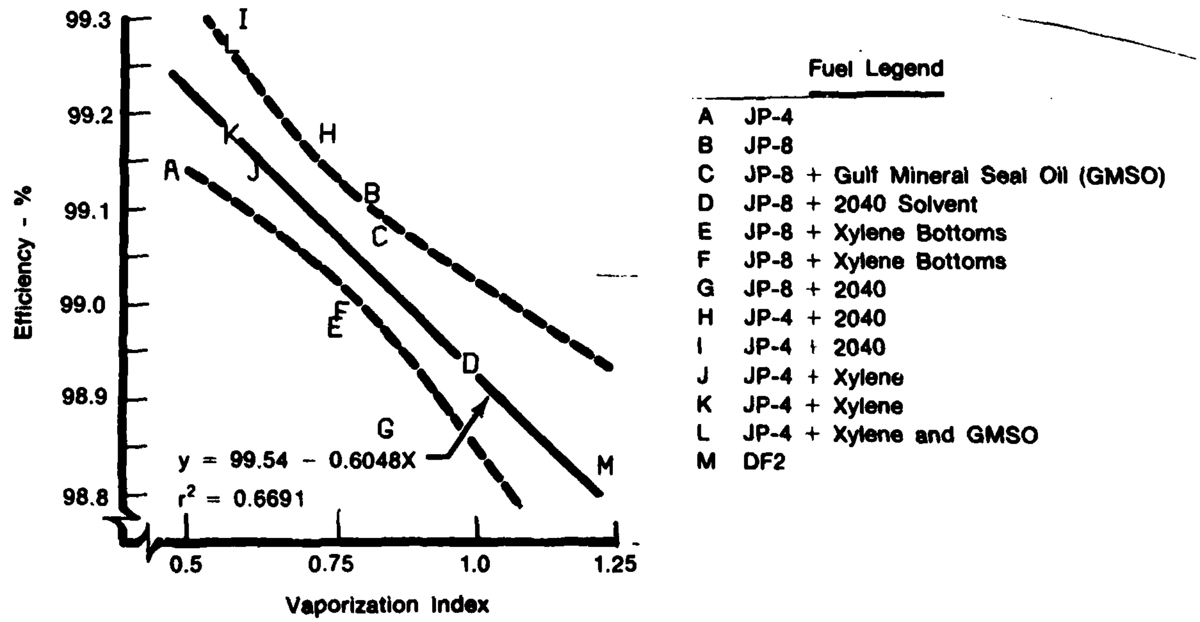


Figure 18. F101 Combustion Efficiency at Idle

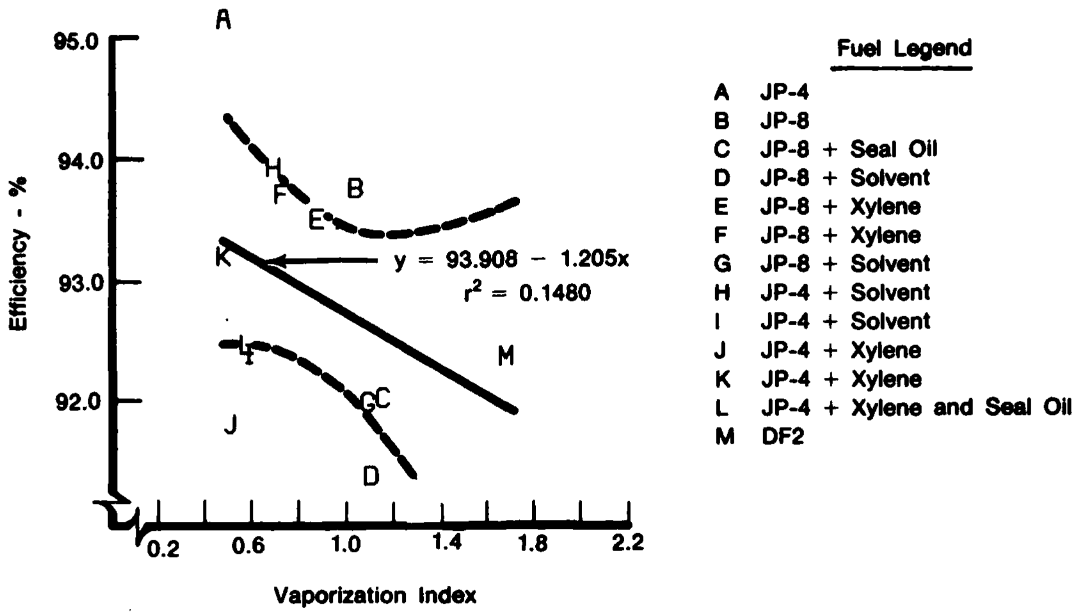


Figure 19. J79-17C Combustion Efficiency at Idle

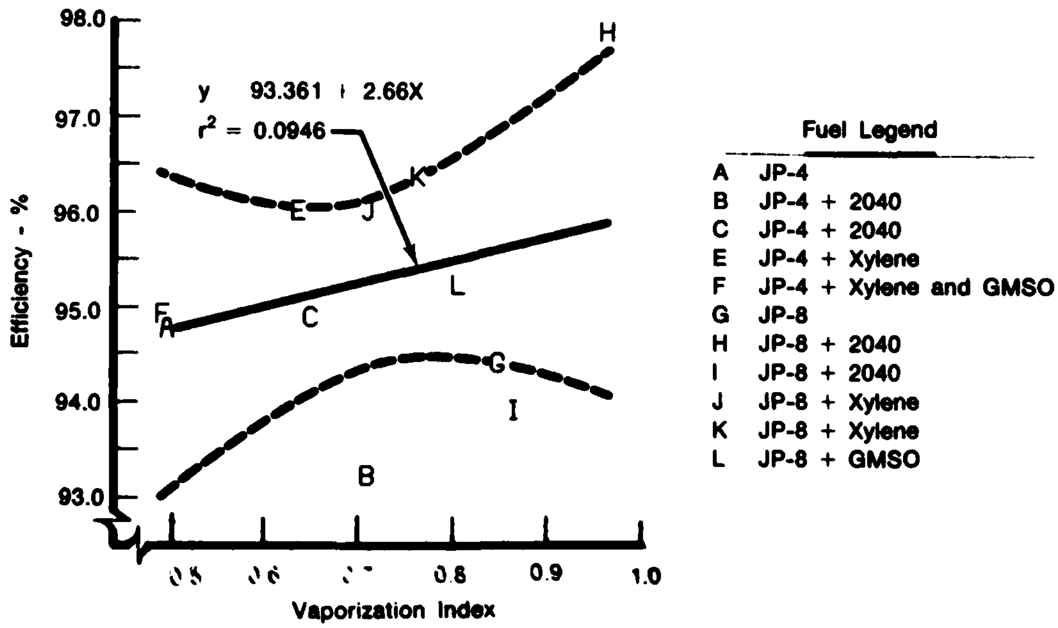


Figure 20. TF41 Combustion Efficiency at Idle

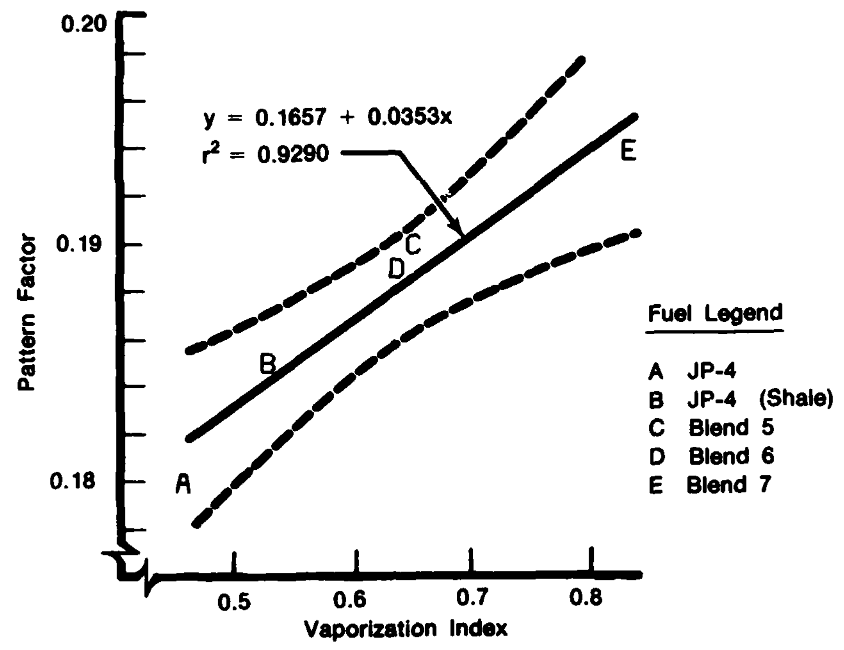


Figure 21. F100 Pattern Factor at SLTO

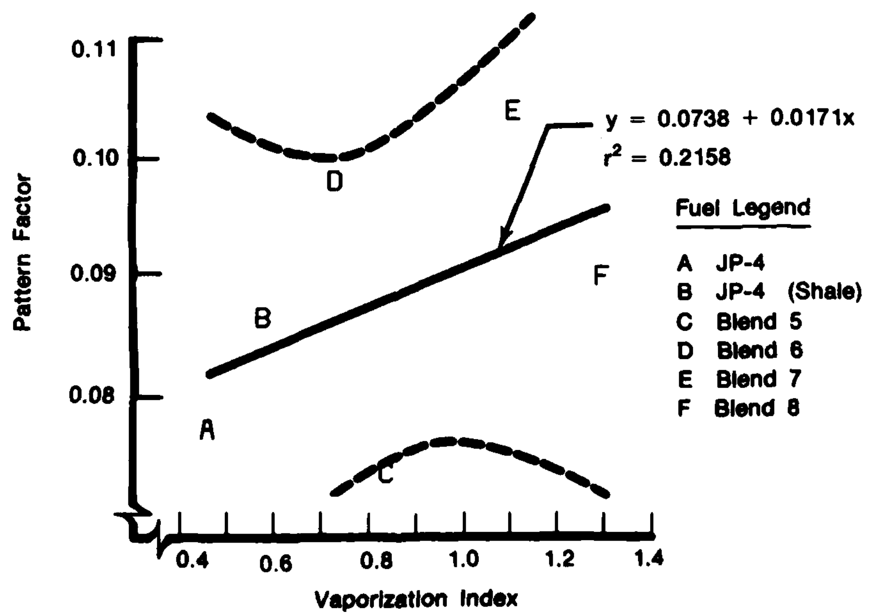


Figure 22. TF33 Pattern Factor at SLTO

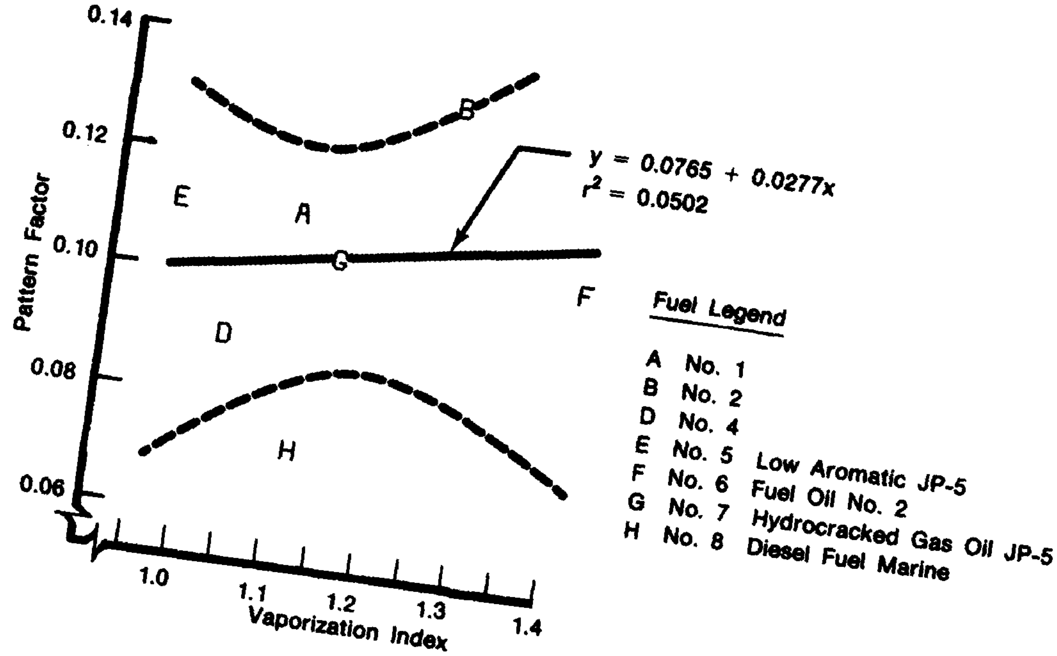


Figure 23. TF30 Pattern Factor at SLTO

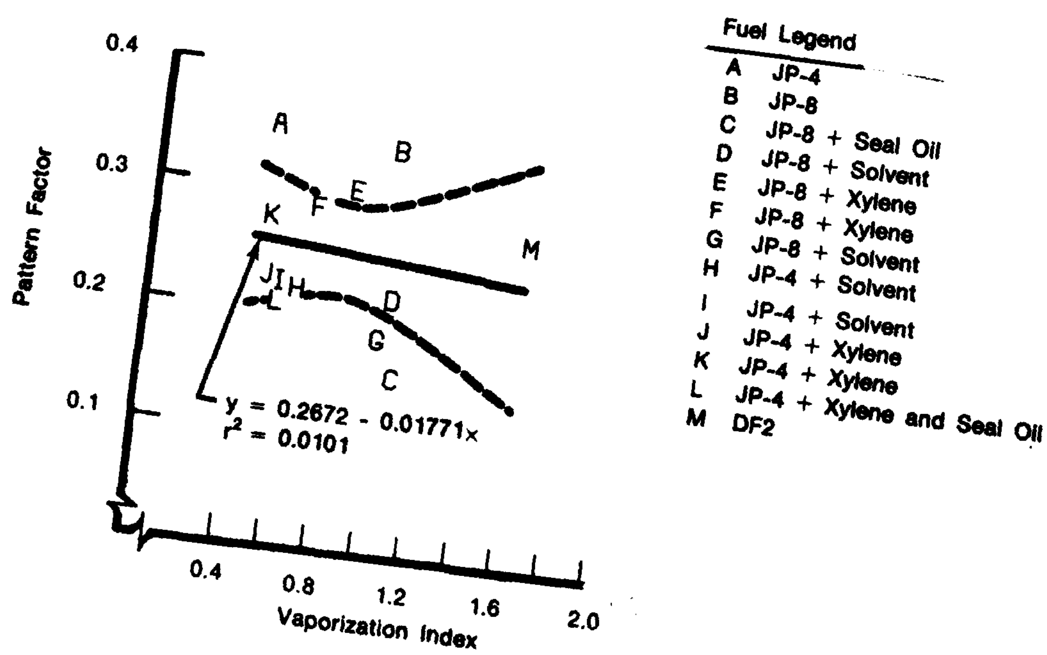


Figure 24. J79-17C Pattern Factor at SLTO

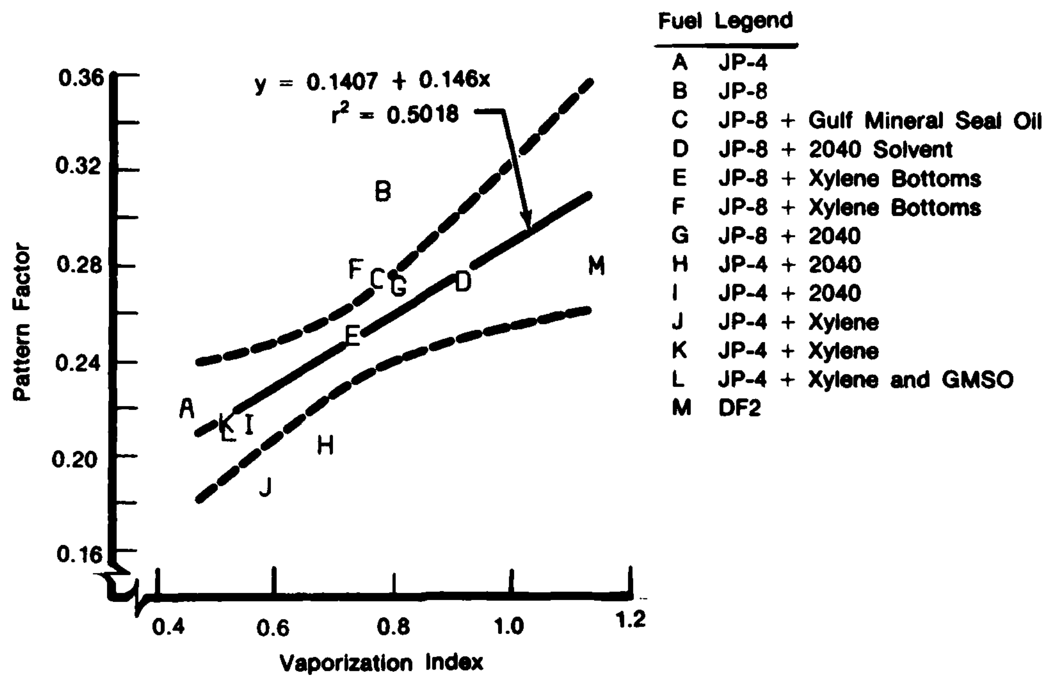


Figure 25. F101 Pattern Factor at SLTO

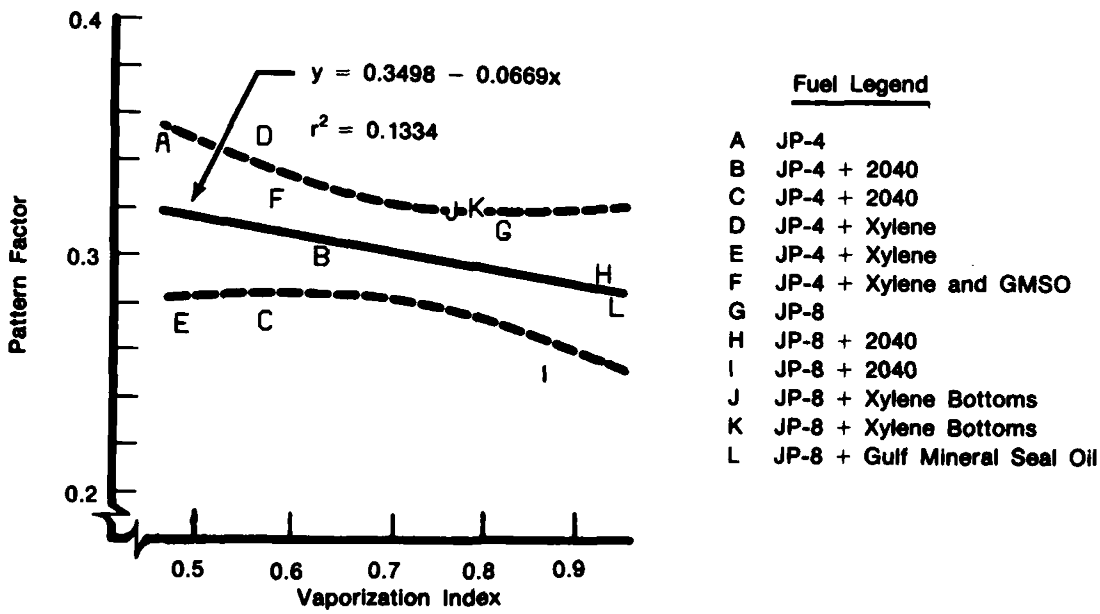


Figure 26. TF41 Pattern Factor at SLTO

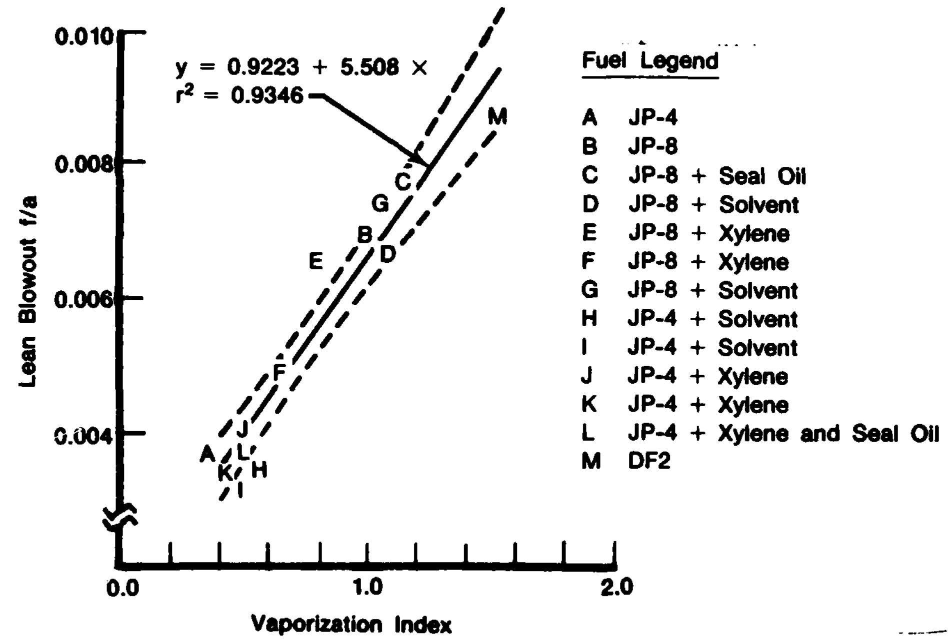


Figure 27. Effect of Vaporization Index on J79-17C Lean Blowout Fuel-Air Ratio

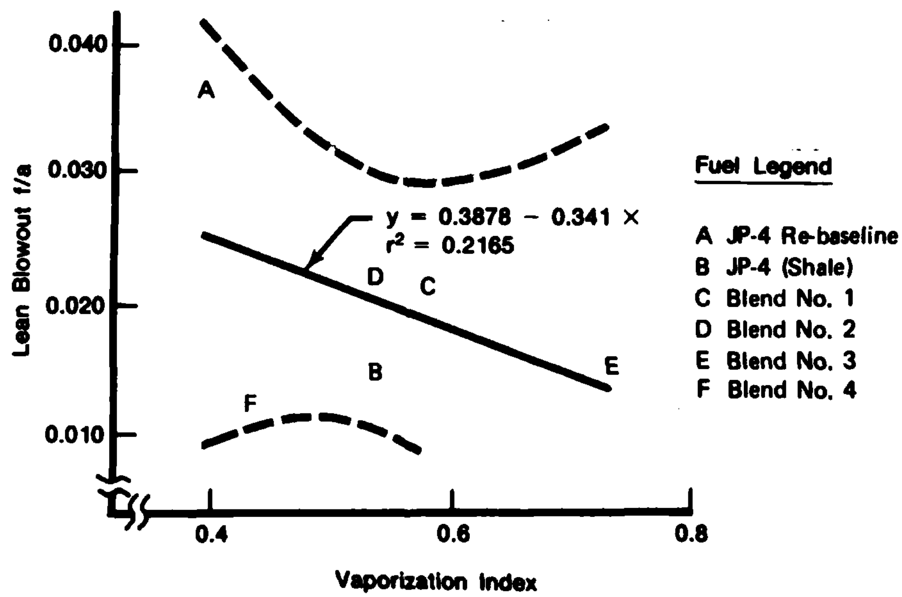


Figure 28. Effect of Vaporization Index on TF33 Lean Blowout Fuel-Air Ratio

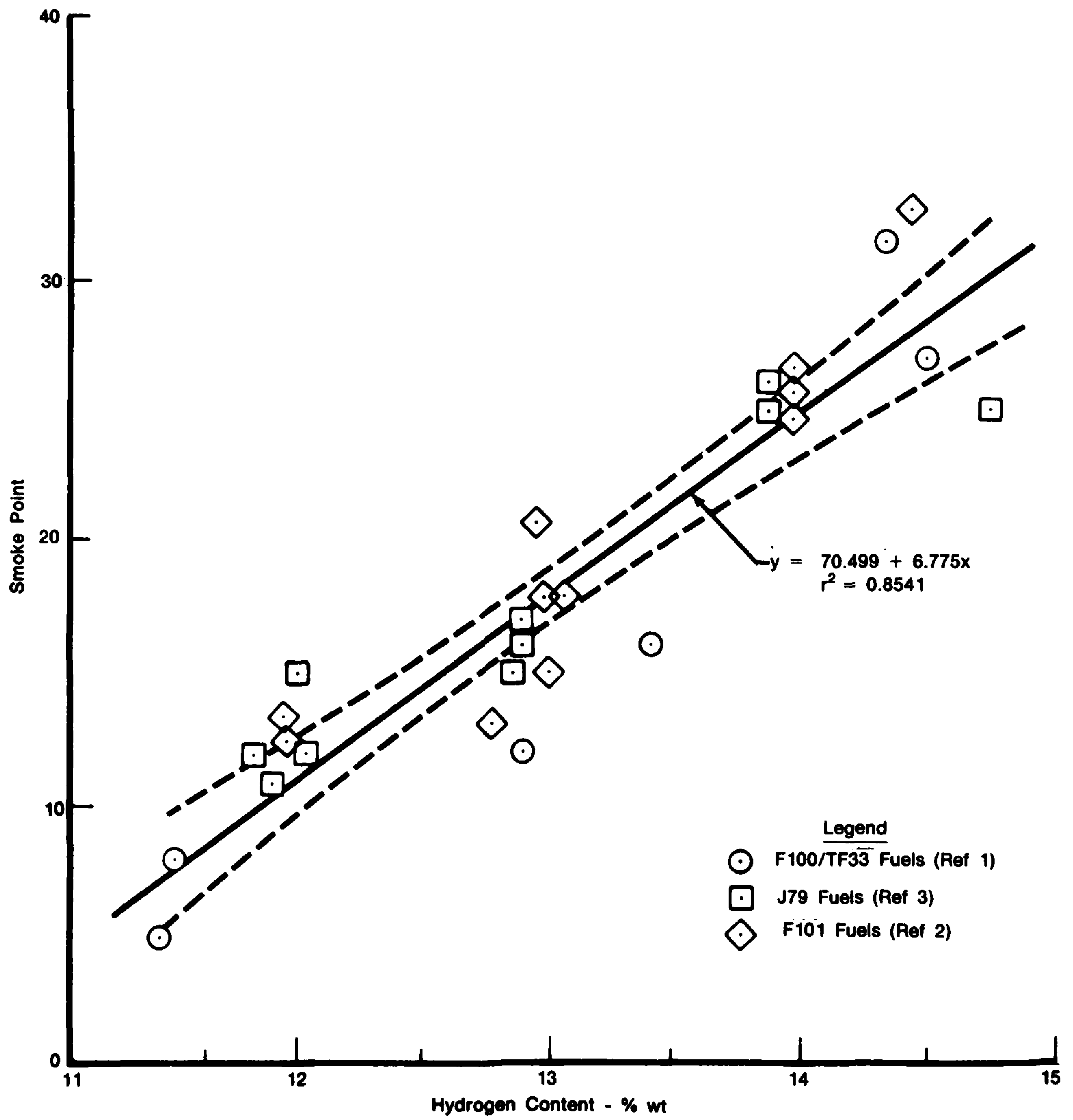


Figure 29. Smoke Point vs Hydrogen Content for the F100, TF33, F101, and J79-17C Test Fuels

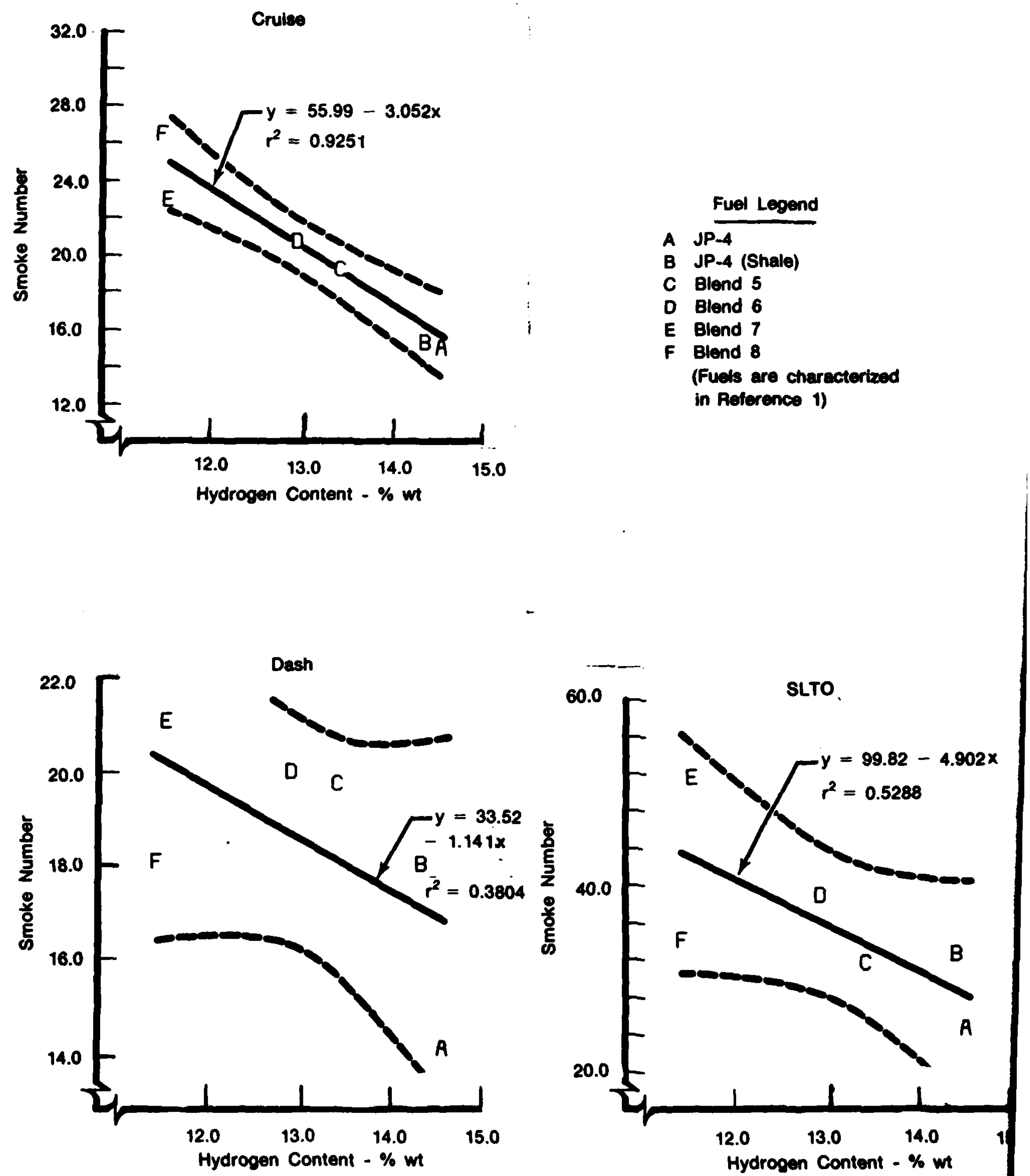


Figure 30. F100 Smoke Number/Fuel Property Correlation

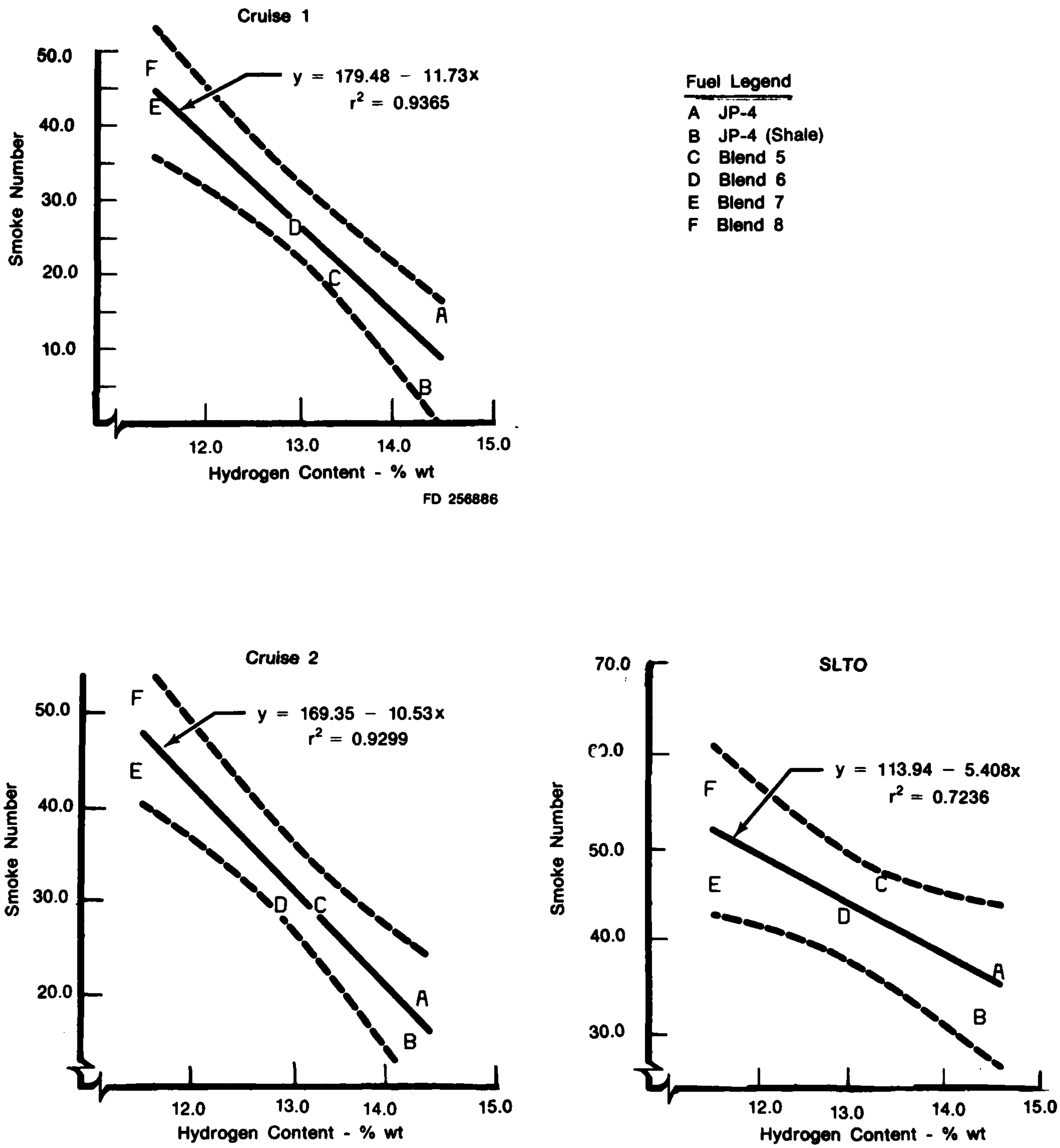


Figure 31. TF33 Smoke Number/Fuel Property Correlation

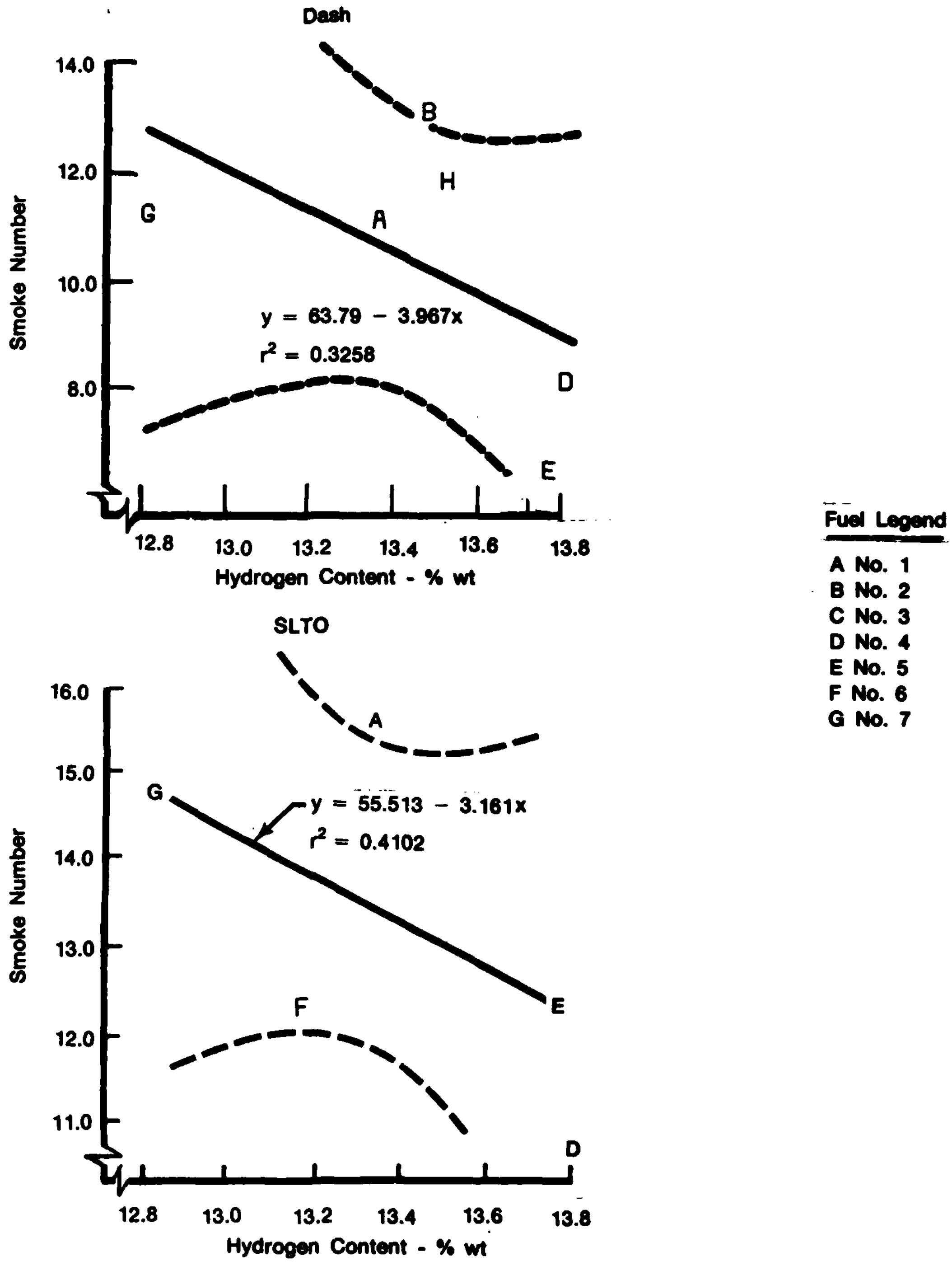


Figure 32. TF30 Smoke Number Correlation

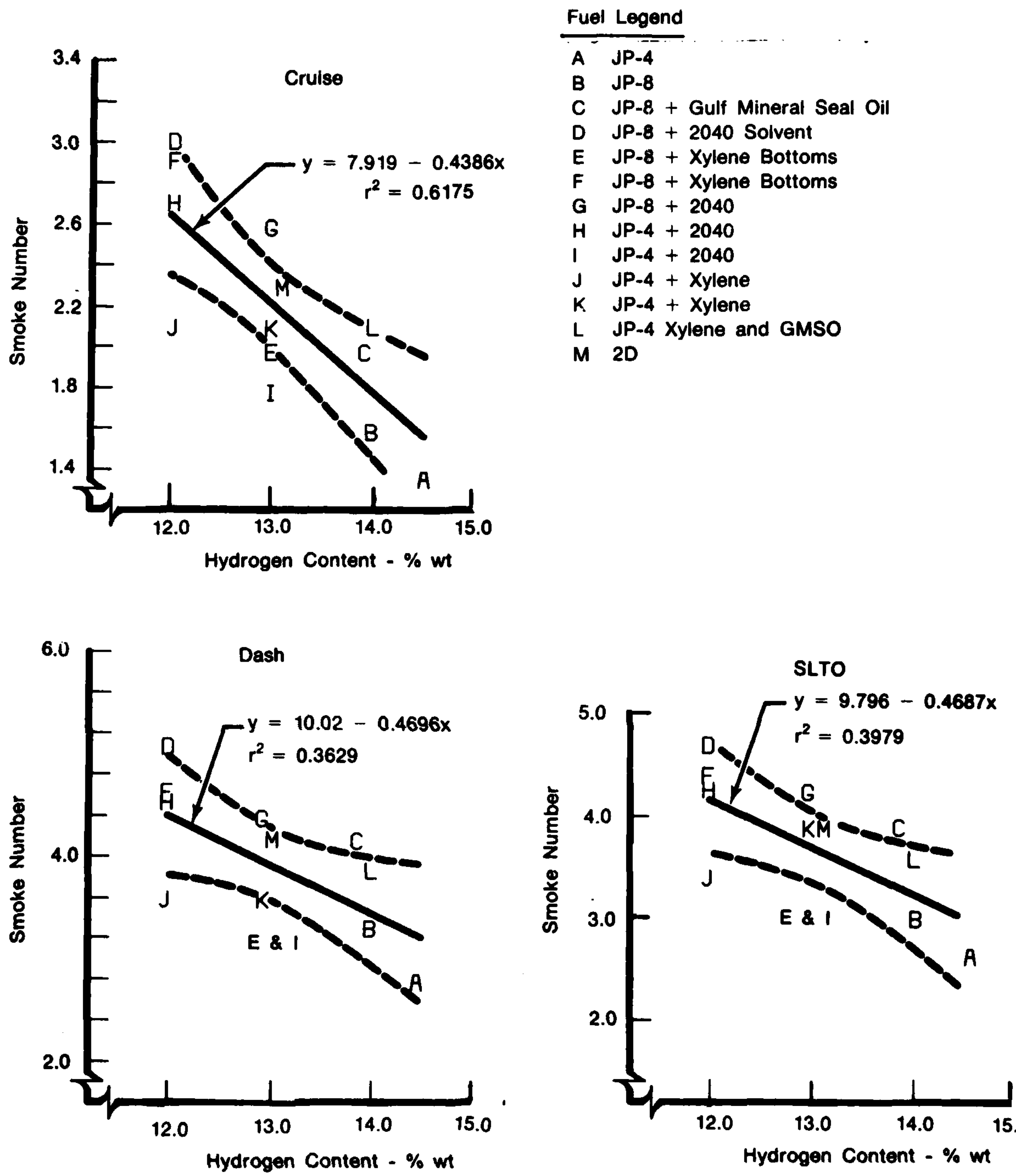


Figure 33. F101 Smoke Number/Fuel Property Correlation

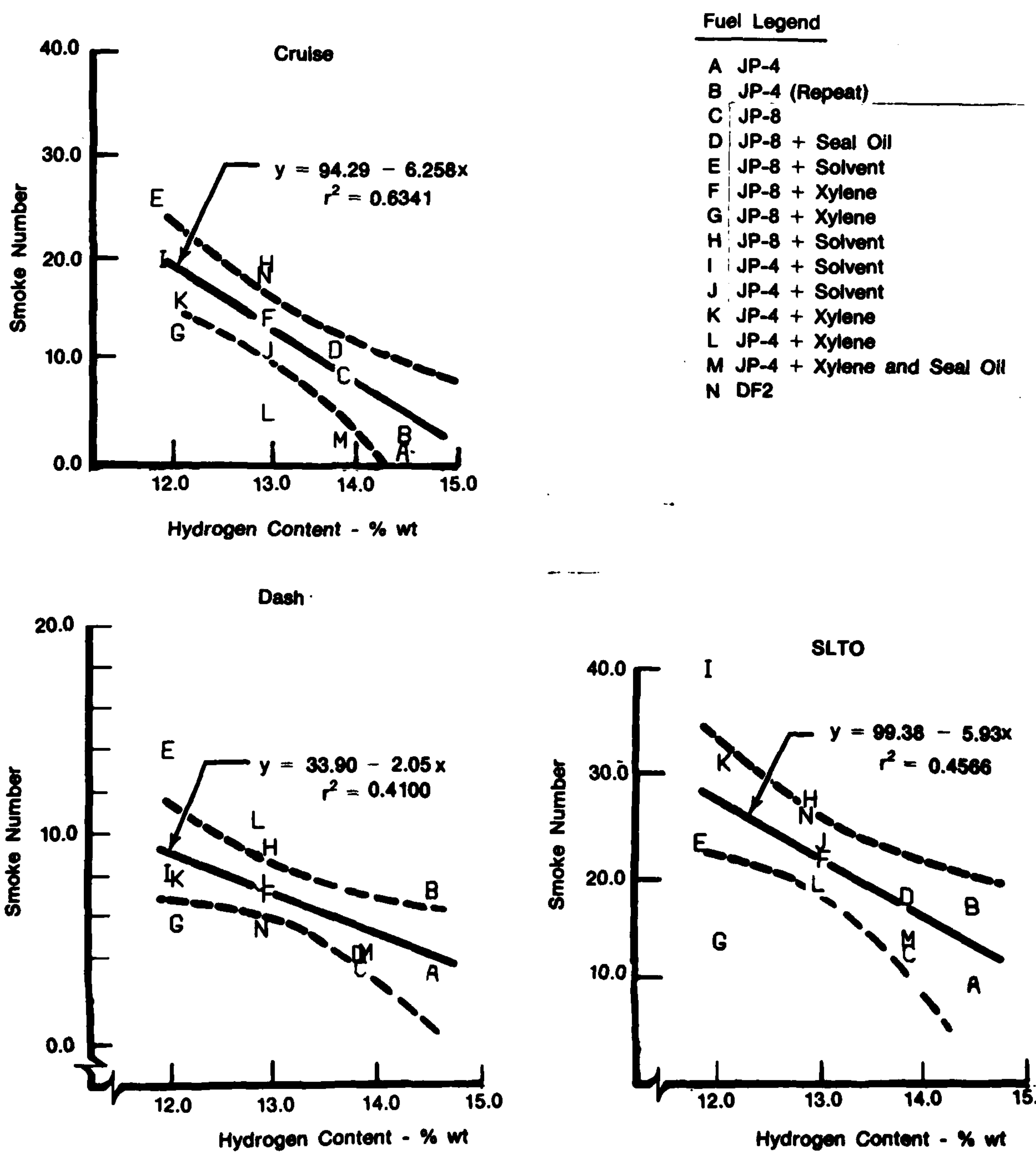


Figure 34. J79-17C Smoke Number/Fuel Property Correlation

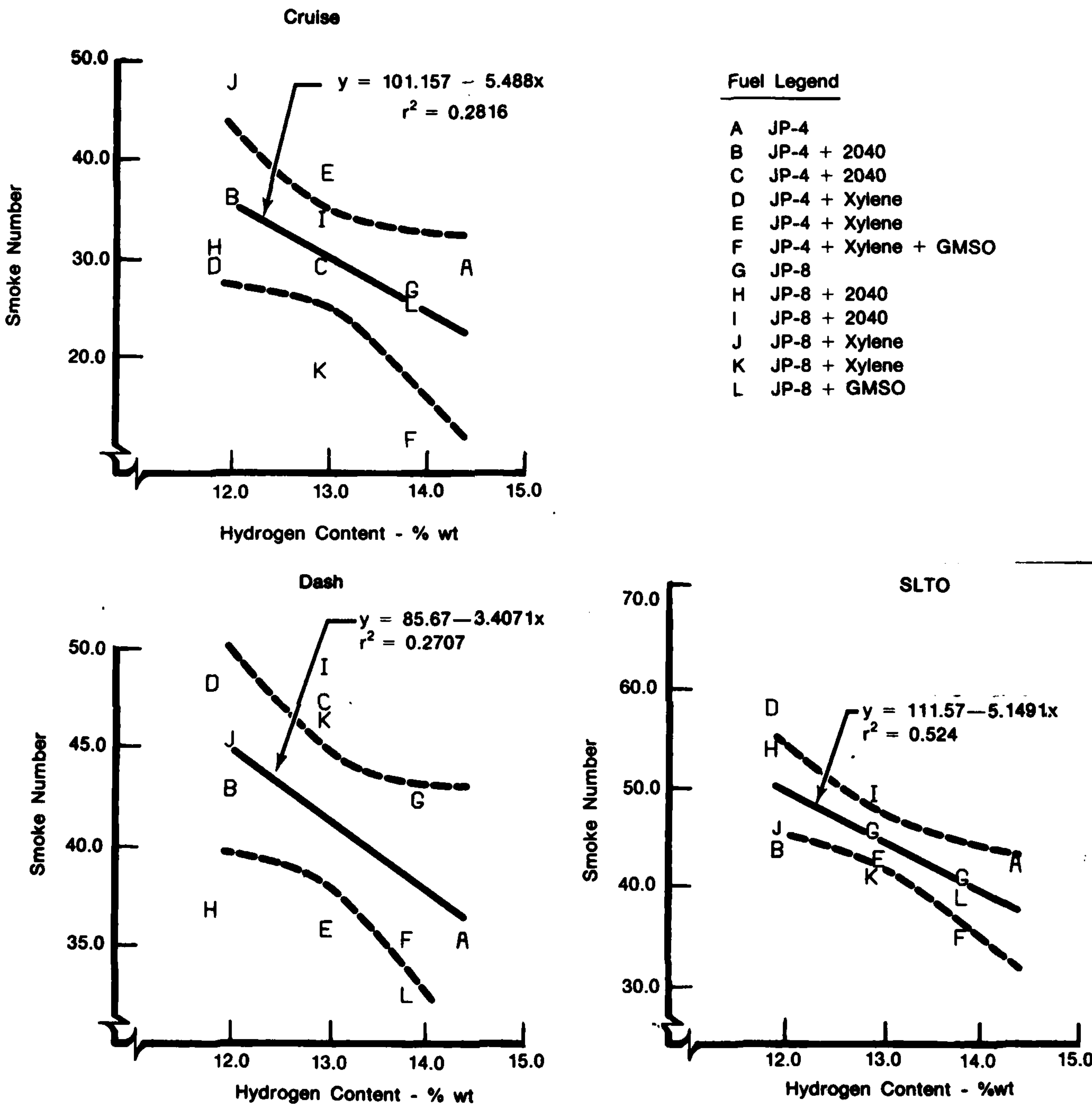


Figure 35. TF41 Smoke Number/Fuel Property Correlation

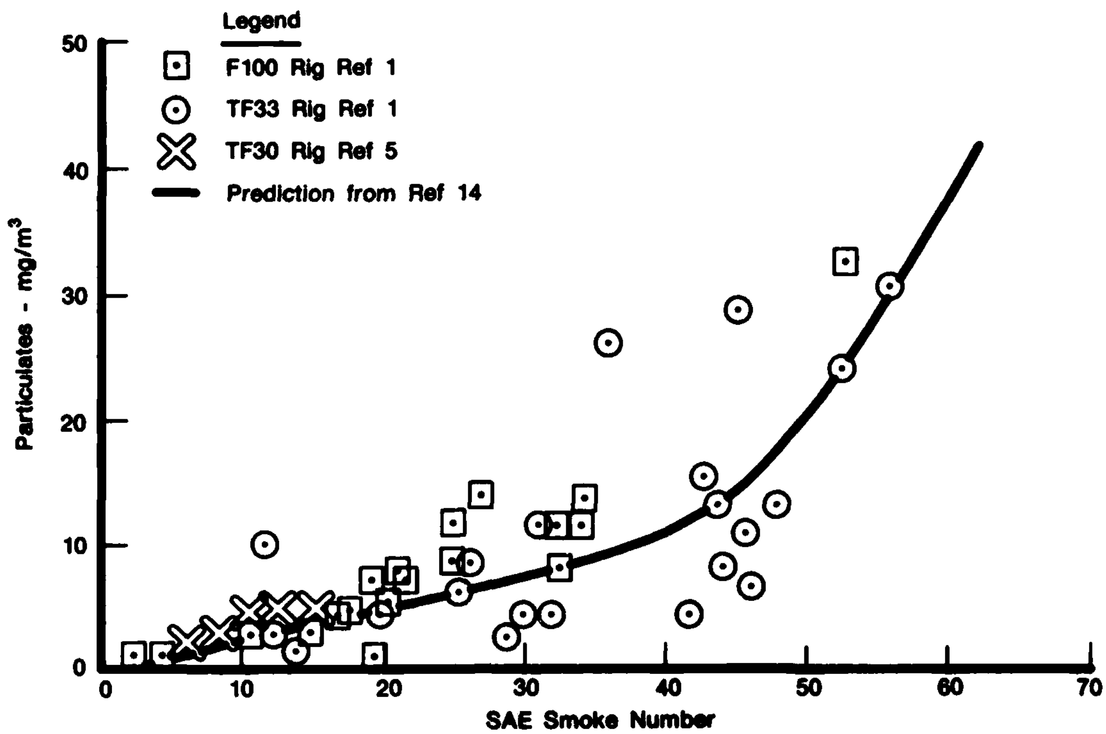


Figure 36. Correlation of Particulate Concentration With SAE Smoke Number

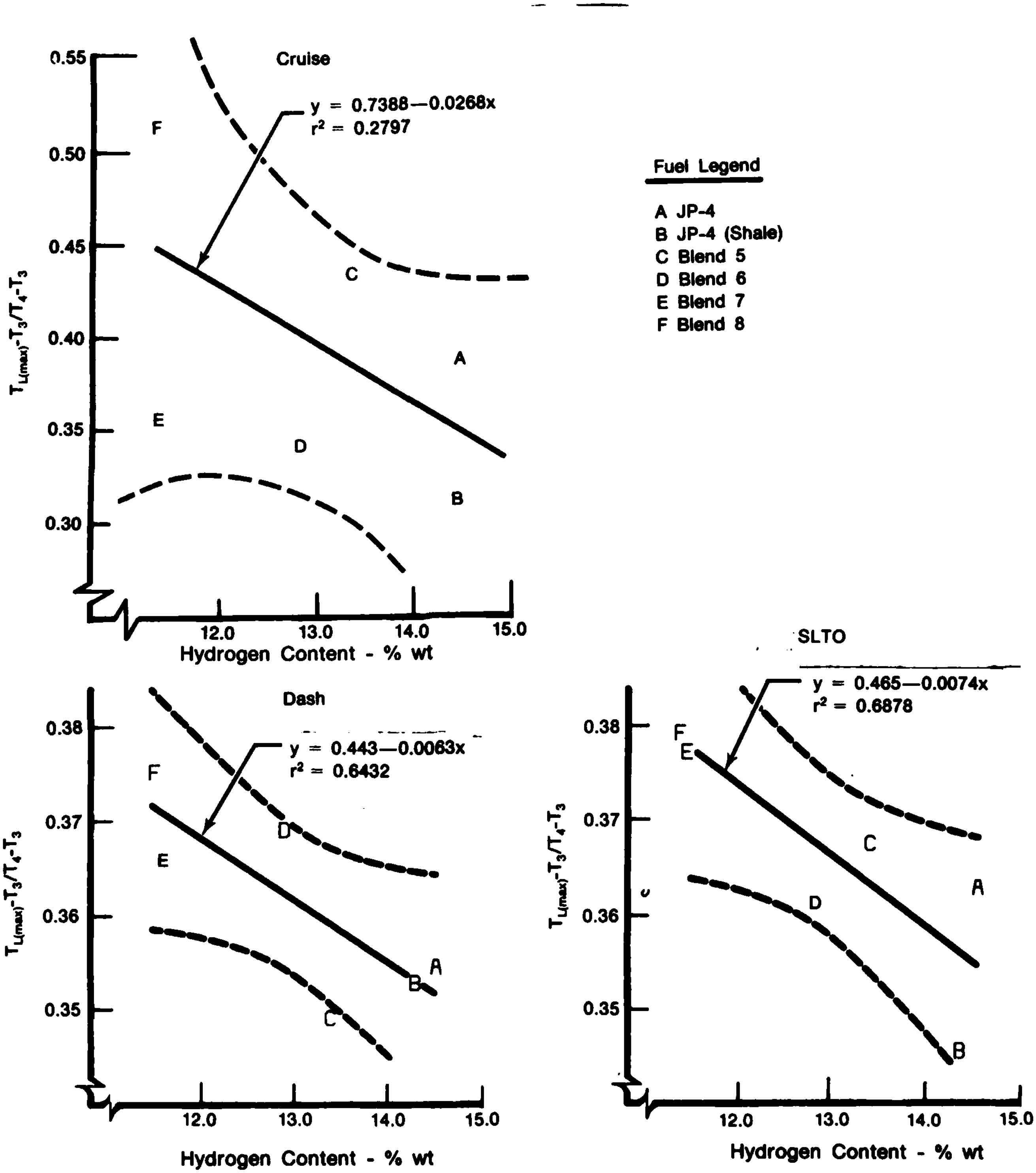


Figure 37. F100 Liner Temperature Correlation

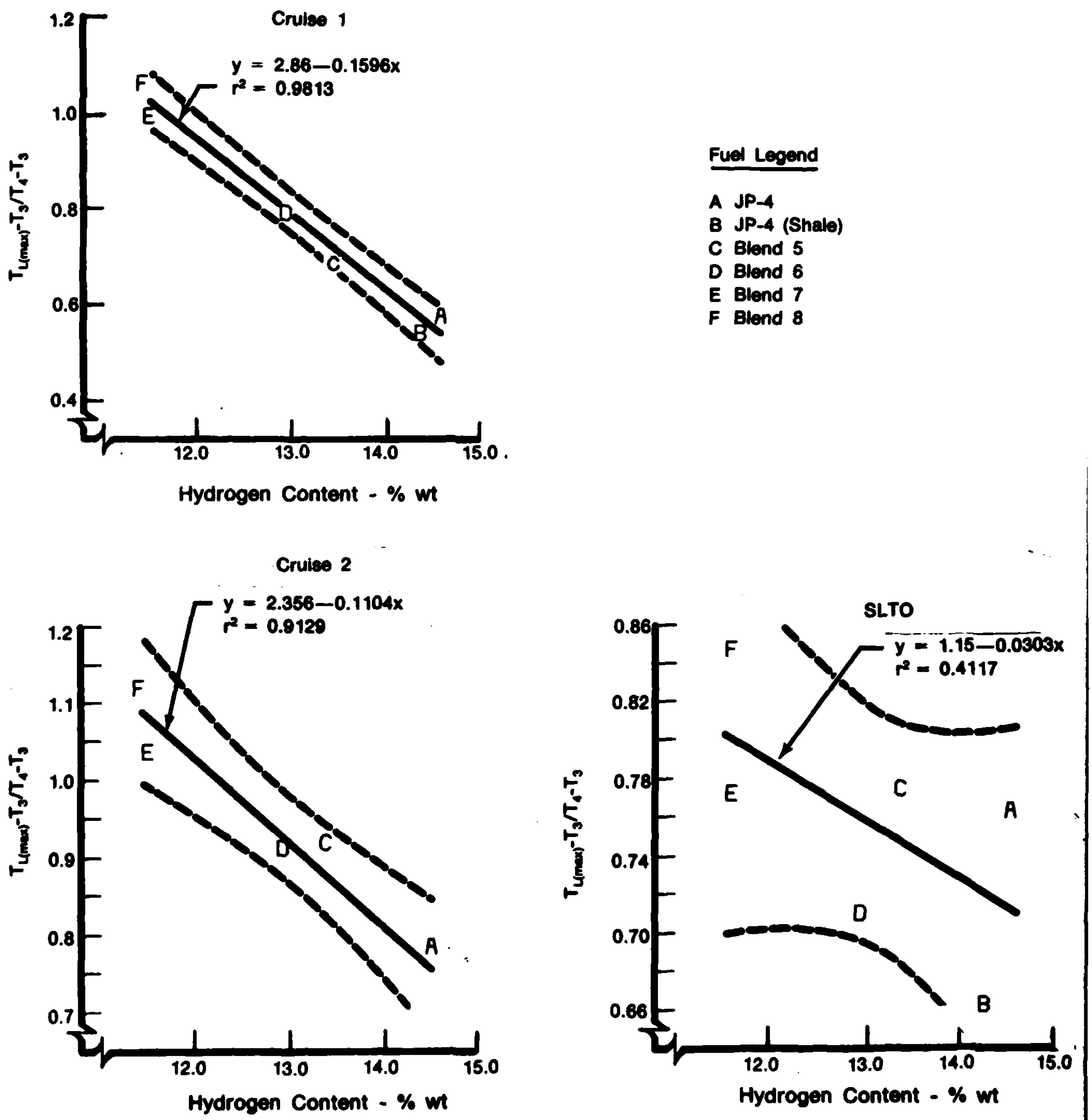


Figure 38. TF33 Liner Temperature Correlation

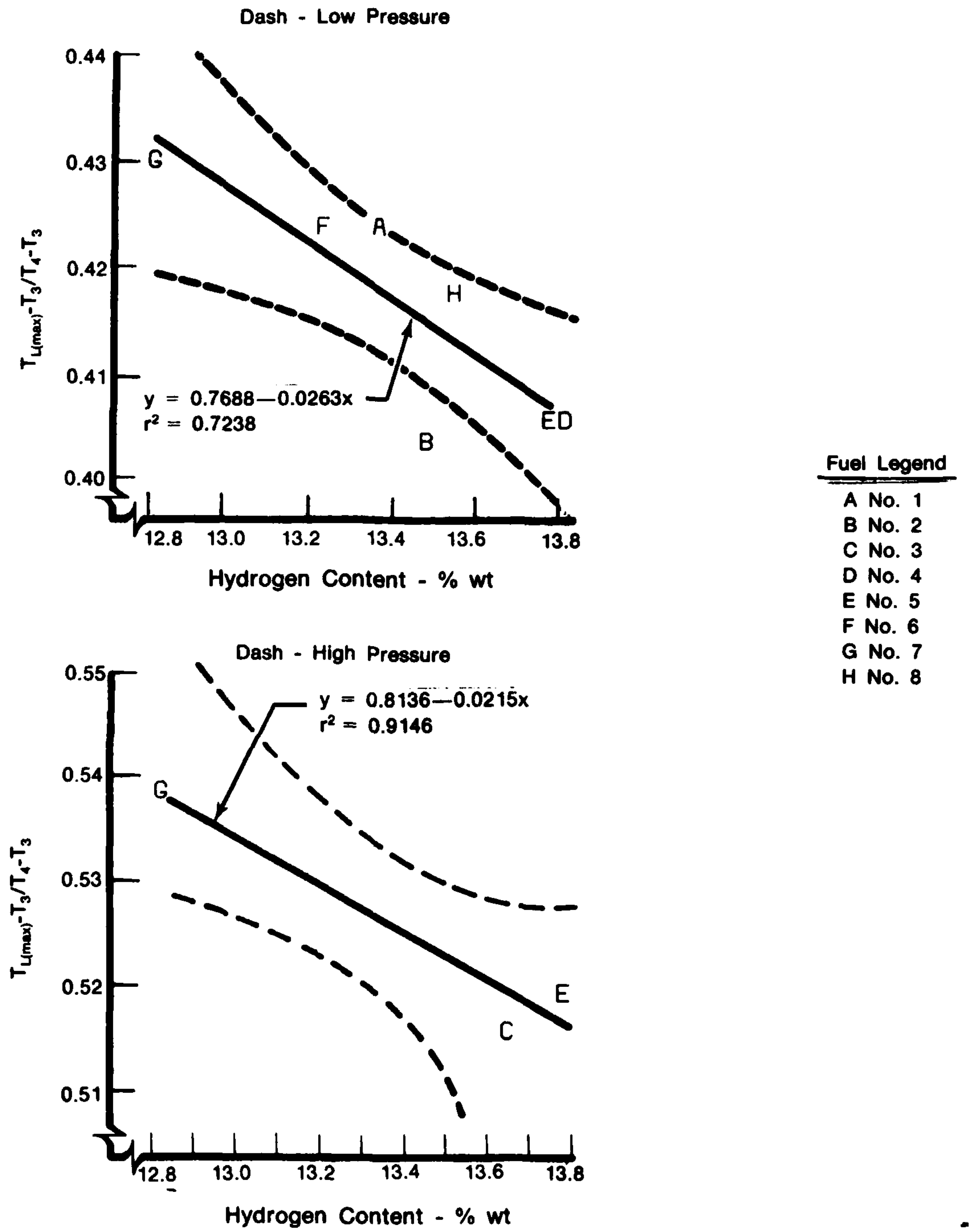


Figure 39. TF30 Liner Temperature Correlation

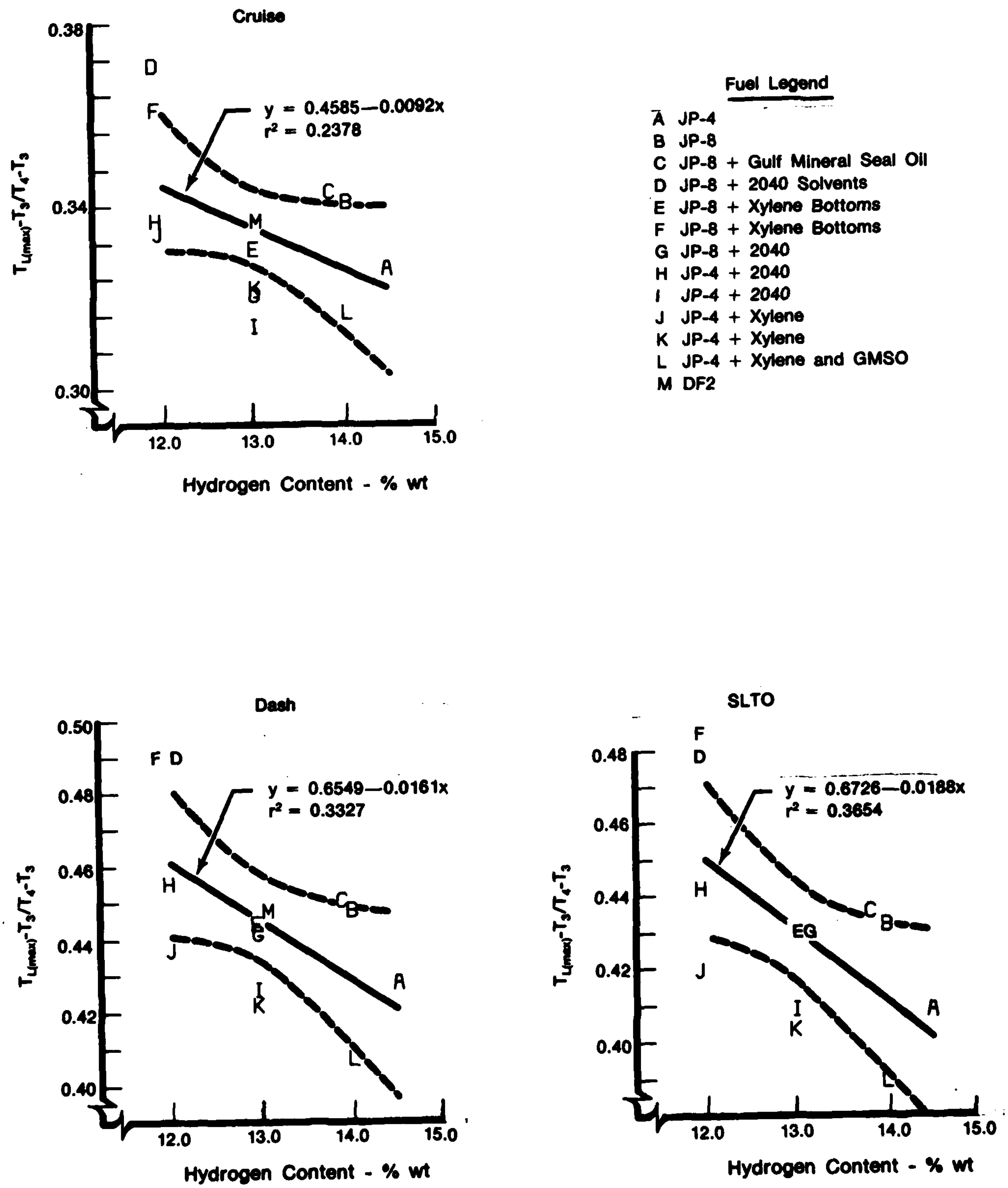


Figure 40. F101 Liner Temperature Correlation

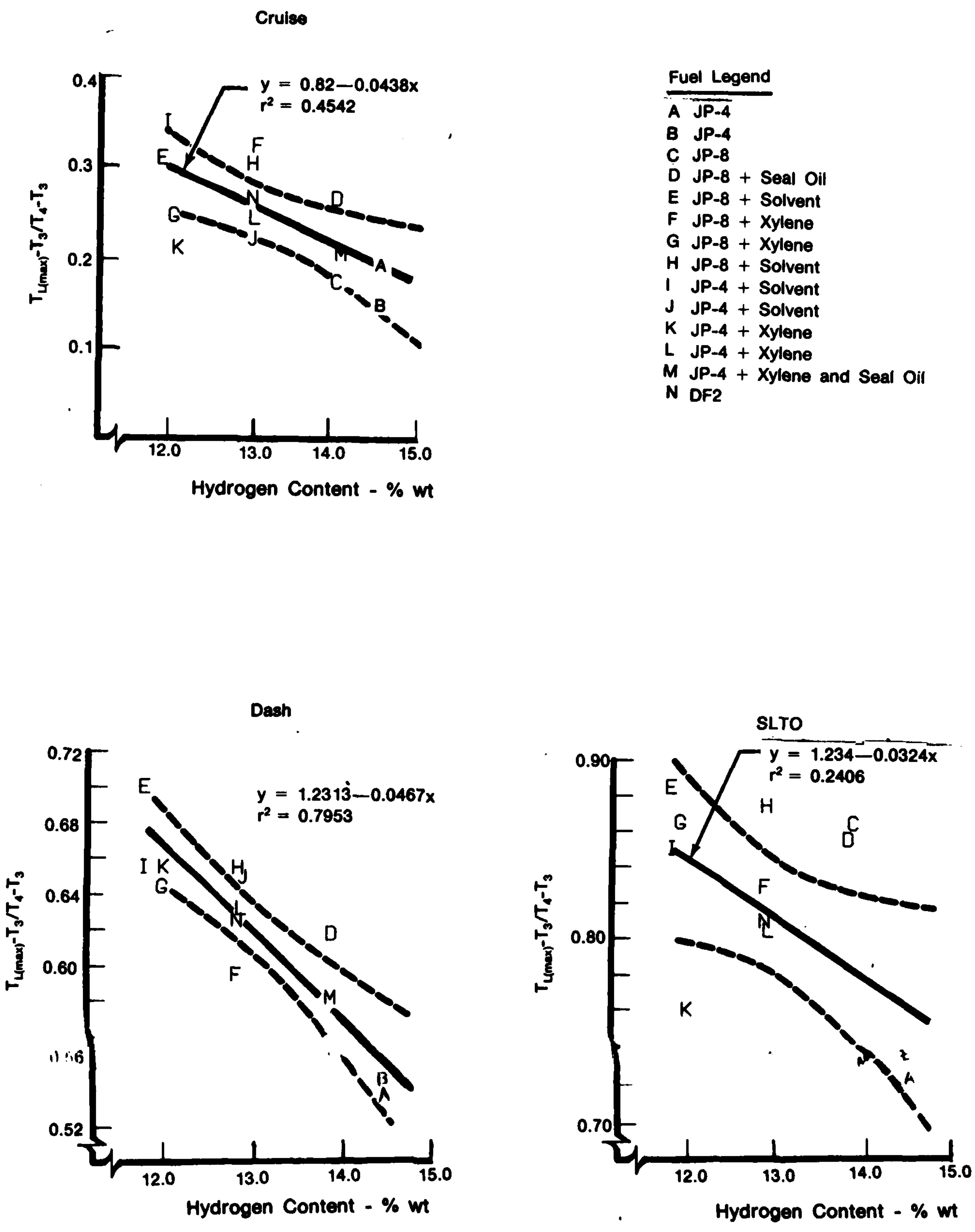


Figure 41. J79-17C Liner Temperature Correlation

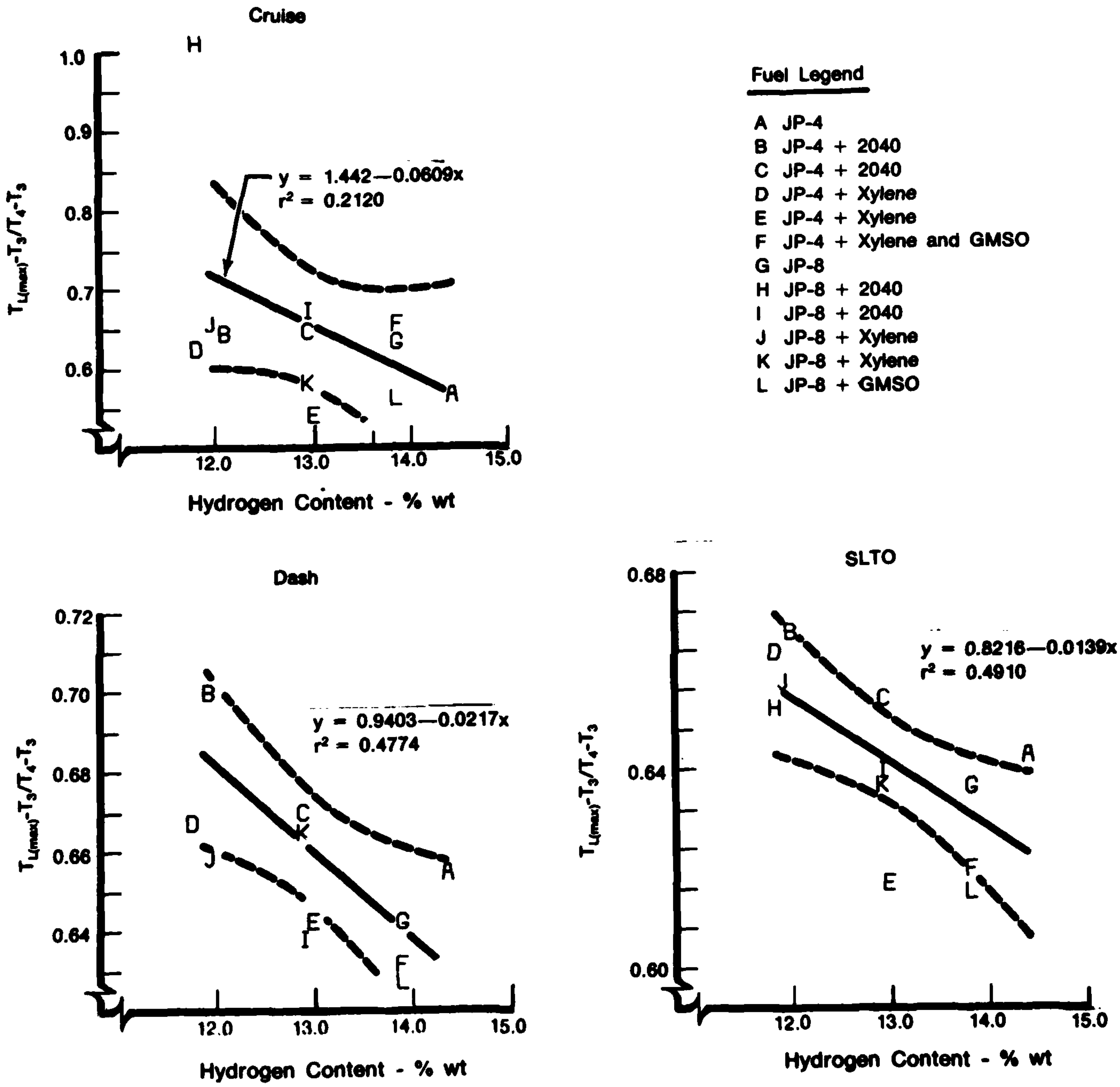


Figure 42. TF41 Liner Temperature Correlation

SECTION IV

ENGINE DESIGN AND OPERATING CHARACTERISTICS CORRELATIONS

A. ALTITUDE RELIGHT CORRELATIONS

The evaluation of fuel property effects on altitude relight capability was presented in Section III-B, where the correlation groups of fuel characteristic parameter (FCP) and combustor operating parameter (COP) were developed. The original objective was to separate the various parameters of interest into the two groups, i.e.: (1) fuel properties, and (2) combustor geometry and operating condition terms.

The problem which arises from this approach is that the FCP term contains the Sauter mean diameter (SMD) of the fuel spray, and the SMD contains engine design as well as fuel property variables. The manner in which the fuel properties affect SMD varies, depending on the type of fuel nozzle employed in the design. For this reason, the engines were separated into the three following classes depending on the fuel nozzle type:

1. Pressure atomizing
2. Airblast
3. Hybrid.

The fuel effect data which were used for this portion of the study were taken from F100, F101, TF30, TF33, and J79 combustor tests. The F100 and F101 utilize forms of airblast fuel nozzles, the TF30 and TF33 use pressure atomizing fuel nozzles, and the J79-17C is a hybrid design. The FCP and COP which is used in each of these three groups depends on the fuel nozzle type. The pressure atomizing and airblast designs utilize the previously defined (Section III-B) equations to predict SMD and hence, FCP and COP.

The general equation for COP has been modified from the earlier equation to account for the variation in COP with engine airflow. The resultant equations are:

$$FCP = \frac{\rho_f (SMD)^{1.5}}{\ln(1 + B)} \tag{19}$$

$$COP = \frac{Pr_a (Tu/100)^{.5} U^{.5}}{\rho_a^{.5} \mu_a^{.5} \phi \, W_a} \tag{20}$$

where:

ρ_f	fuel density	g/cc
SMD	Sauter mean diameter	m^{-6}
B	Spalding mass transfer number	
Pr_a	Air Prandtl number	
Tu	Turbulence intensity	%
U	Air velocity	m/s
ρ_a	Air density	g/cc
μ_a	Air viscosity	$N/m^2 \cdot s$
ϕ	Equivalence ratio	
W_a	Combustor air flow	kg/s

For fuel nozzles where a usable correlation of SMD vs fuel properties was not available, (eg. J79-17C), this equation set may be used directly. The results of the previous fuel effects correlation are shown in Figure 43. The data scatter which is observed is typical of the results for the altitude relight data. This figure may be used directly to evaluate fuel effects for a design where the user is aware of the effect of the properties on the SMD.

For a design where an equation for SMD as a function of fuel properties is available e.g., pressure atomizing and airblast fuel nozzles, the various fuel properties may be introduced into FCP and COP directly.

For pressure atomizing fuel nozzles, the resulting equations are:

$$\mathrm{FCP} = \frac{\rho_f \nu_f^{.3} \sigma_f^{.9}}{\ln(1 + B)} \tag{21}$$

$$\mathrm{COP} = \frac{\mathrm{Pr}_a (\mathrm{Tu}/100)^{.5}\, \mathrm{U}^{.5}\, \mathrm{W}_f^{.375}}{\rho_a^{.5}\, \mu_a^{.5}\, \phi\, \Delta \mathrm{P}_f^{.6}\, \mathrm{W}_a} \tag{22}$$

where:

ν_f	=	fuel kinematic viscosity	m^2/s
σ_f	=	fuel surface tension	N/m
ΔP_f	=	fuel pressure drop	kPa
W_f	=	fuel flowrate	kg/s.

Test data from the TF30 and TF33 are shown in Figures 44 and 45. The figures are based on COP from Figures 1 and 3 divided by the air flowrate. The two curves were normalized with reference to JP-4 fuel properties and plotted in Figure 46. A regression equation is shown which can be used to evaluate the fuel properties effects on altitude relight capability for pressure atomizing fuel nozzle combustors. The majority of the data are within ±10% of the regression line.

The same approach was used for the airblast fuel nozzle designs where the SMD was related to fuel properties and operating conditions. This yielded the following equations:

$$\mathrm{FCP} = \frac{\rho_f^{1.15}\, \sigma_f^{.9}}{\ln(1 + B)} \tag{23}$$

$$\mathrm{COP} = \frac{\mathrm{Pr}_a (\mathrm{Tu}/100)^{.5} \mathrm{U}^{.5} (1 + \mathrm{W}_f/\mathrm{W}_a)^{1.5}}{\rho_a^{.65}\, \mu_a^{.5}\, \phi\, \Delta \mathrm{P}_a^{.9}} \tag{24}$$

These equations were applied to the F100 and F101 altitude relight data. The data from the F100 tests were significantly more scattered than the F101. The same trend was basically observed but the scatter was excessive for use in this correlation. The F101 data showed the typical 10 to 15% scatter and were used as representative of airblast fuel nozzle behavior. The results are shown in Figure 47. These data should be used to define the fuel properties effects on altitude relight for airblast fuel nozzle combustors.

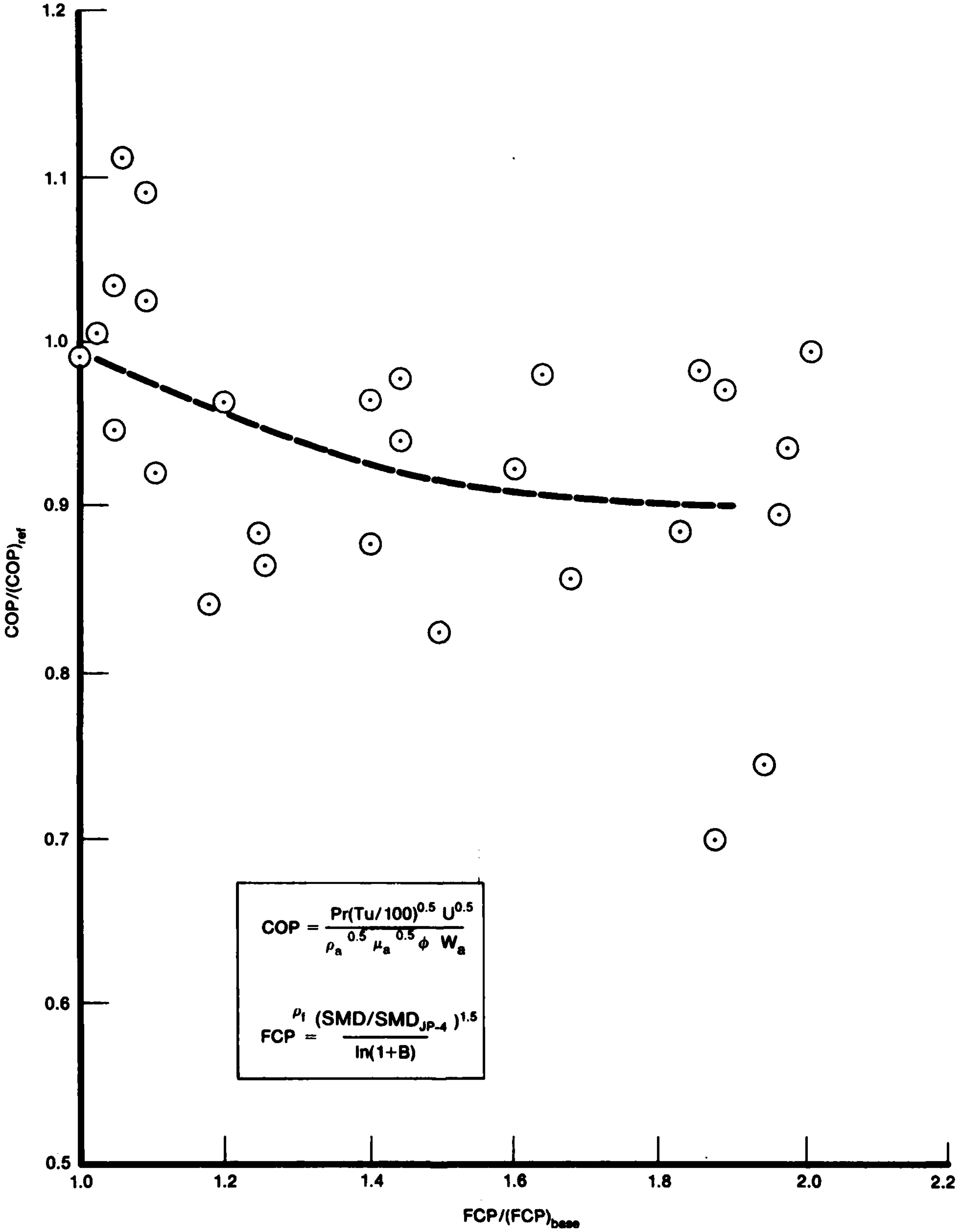


Figure 43. Basic Altitude Relight Correlation With J79-17C Data

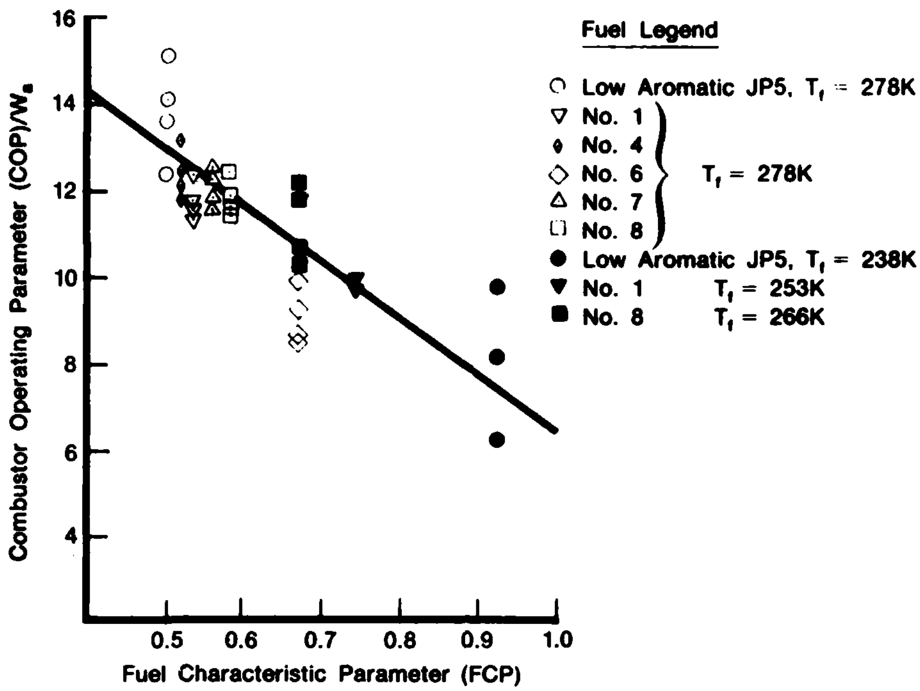


Figure 44. TF30 Altitude Relight Correlation

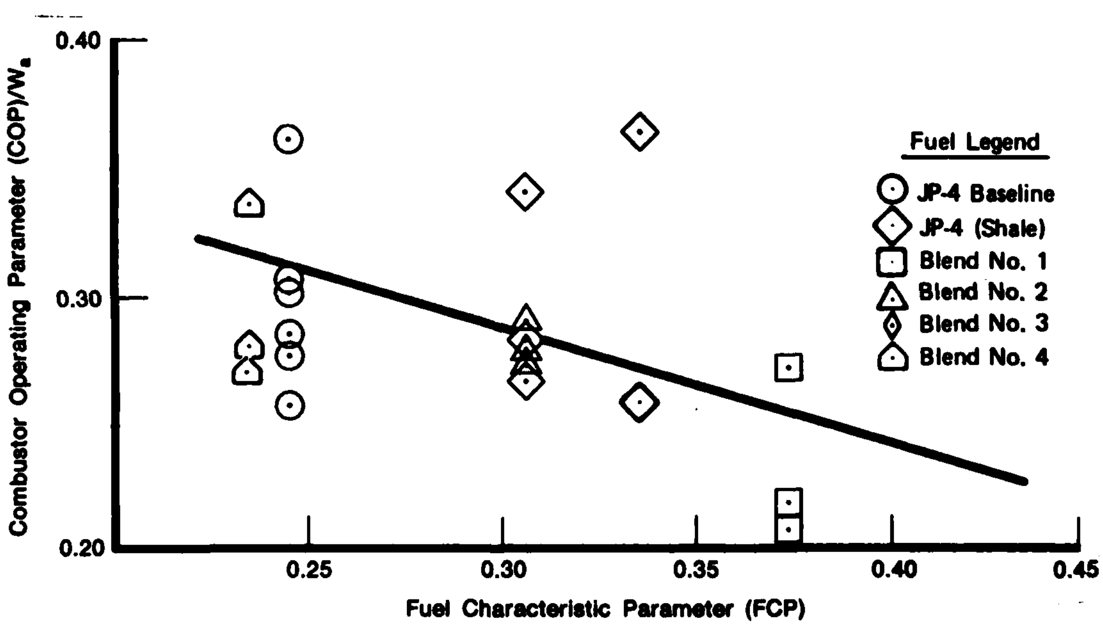


Figure 45. TF33 Altitude Relight Correlation

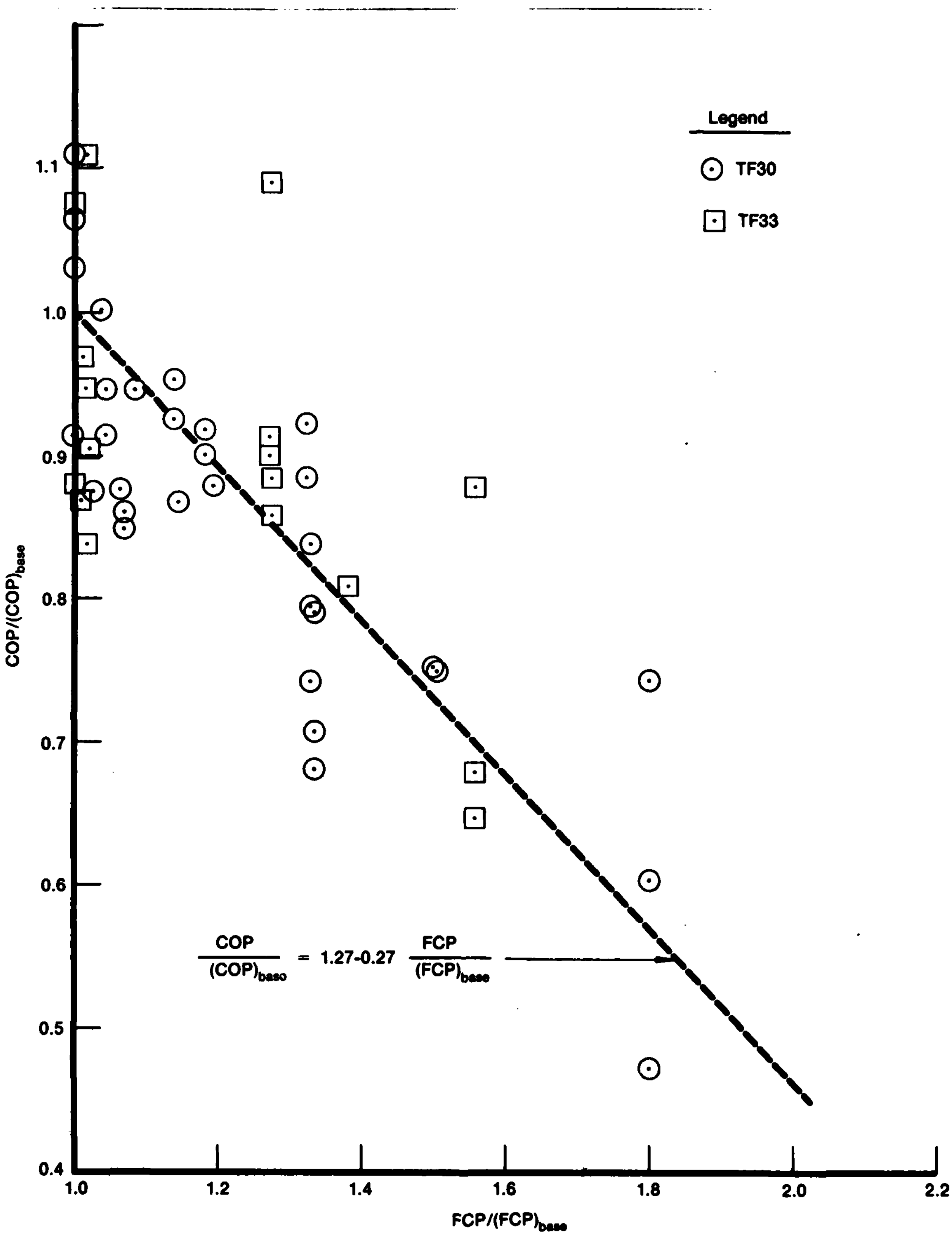


Figure 46. Pressure Atomizing Fuel Nozzle Altitude Relight Correlation

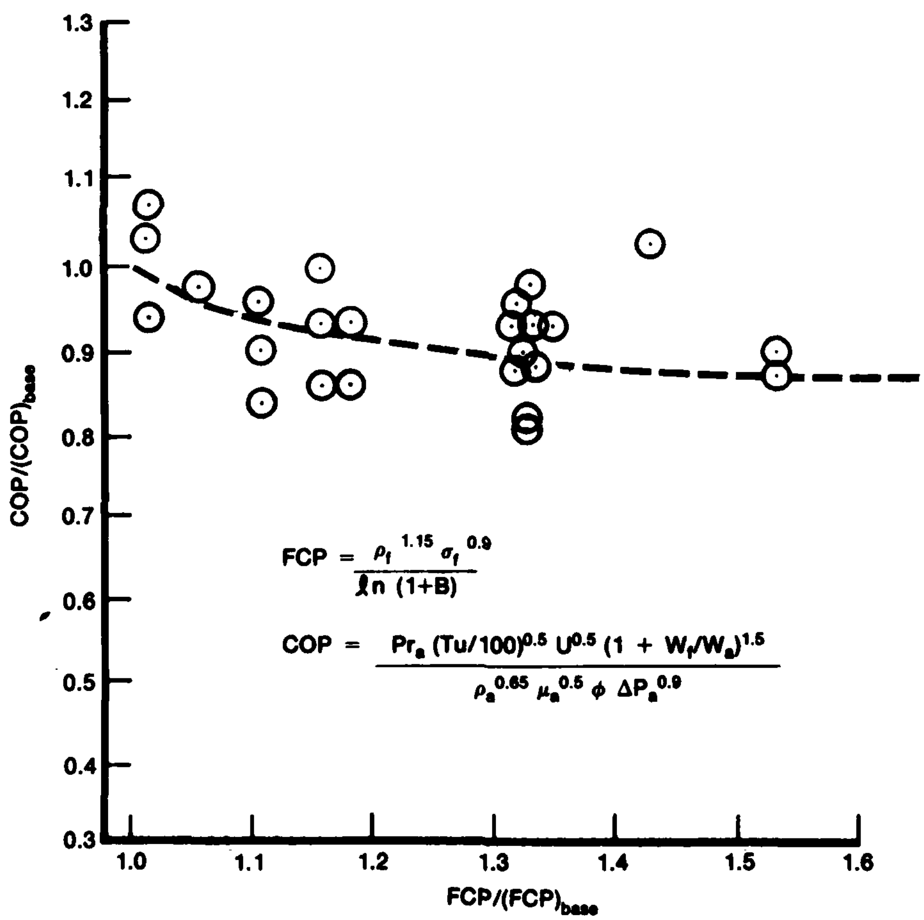


Figure 47. Airblast Fuel Nozzle Altitude Relight Correlation

The application of these three altitude relight correlations to evaluation of the effects of fuel properties variations on the altitude relight capability of a given engine is illustrated below with reference to Figure 48:

1. For a given engine design and known altitude relight limit on a baseline fuel, calculate the baseline fuel properties and engine parameters.

2. For the appropriate fuel nozzle type, calculate the baseline values of FCP and COP.

3. For the new fuel properties, calculate the value of FCP.

4. Using the appropriate fuel effects on altitude relight curve, with the values of FCP and COP for the baseline fuel and FCP for the new fuel, calculate the new value of COP.

5. Using the engine performance map or cycle data, relate the change in COP to changes in relight altitude for a given flight condition.

This procedure is typical of the approach towards evaluation of the effect of variations in fuel properties on not only altitude ignition, but several other engine operating parameters.

B. COMBUSTION EFFICIENCY CORRELATIONS

The effect of fuel properties on relative combustion efficiency is most noticeable at idle conditions. At power levels above this, the combustion improves towards essentially 100% efficiency and no measurable fuel effects are observed.

Based on evaluation of the relationships between combustion efficiency at idle and various fuel properties parameters, the data are best correlated with the vaporization index (VI):

$$VI \ \alpha \ \frac{\rho_f (SMD/SMD_{ref})^2}{\ln(1+B)} \tag{25}$$

Excellent correlations were obtained with data from the F100, TF33, and F101. The data from the TF30, J79 and TF41 showed significant scatter, but consistent trends were identified.

The fundamental principle is that the idle efficiency is controlled by the ability of the final portion of the fuel spray to vaporize rapidly enough to react before leaving the combustor. For this reason, the mass transfer number in VI is evaluated at the appropriate 90% recovery temperature. As the value of VI increases, the tendency to vaporize decreases and the combustion efficiency should also decrease.

This last statement leads to selection of the slope of the regression of efficiency versus vaporization index as the correlation parameter for engine variables. The appropriate results from the fuel properties correlations are shown in Table 11.

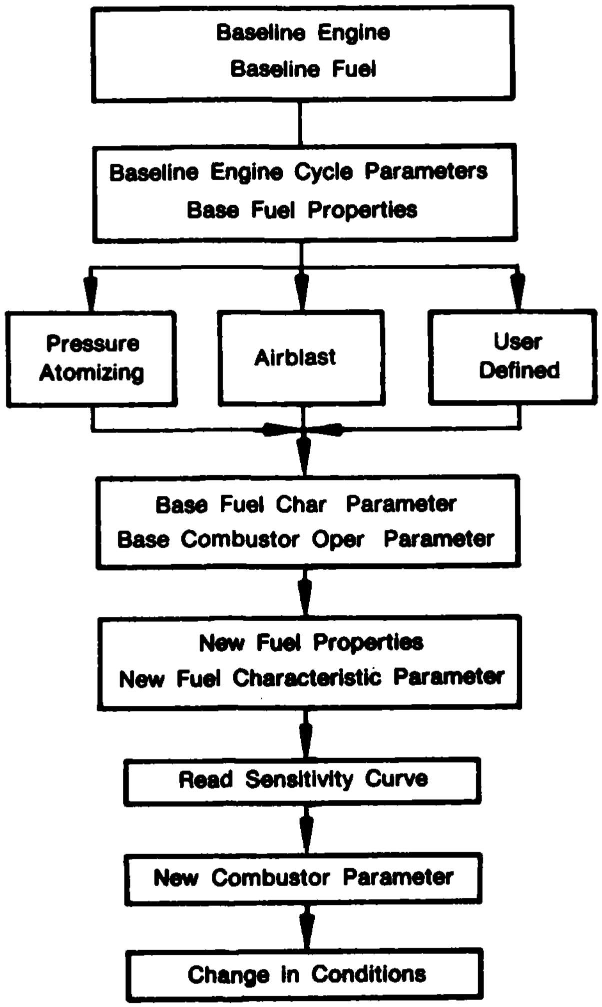


Figure 48. Evaluation of Fuel Effects on Altitude Relight Performance

TABLE 11. RESULTS OF FUEL PROPERTIES CORRELATION WITH IDLE COMBUSTION EFFICIENCY

Engine	*Combustion Efficiency on Base Fuel*	*Slope of Efficiency vs Vaporization Index*
F101	99	−0.60
F100	97.5	−1.92
TF30	95.5	−0.83
J79-17C	93.0	−1.21
TF33	65.0	−4.76
TF41	95.0	2.66

From this table, one obvious conclusion is that the TF41 data show a trend counter to the other fuel effects data. This trend also cannot be supported by theory. These data were therefore omitted from the combustion efficiency correlation.

Evaluating the behavior of the three engines with very good statistical correlations yields:

Engine	Base Efficiency	Slope
F101	99	−0.60
F100	97.5	−1.92
TF33	65.0	−4.76

The trend which is observed is that the lower values of base efficiency are also more sensitive to fuel properties. This is a logical conclusion in that high efficiency implies greater time to accommodate the slower fuel vaporization.

These data are shown in Figure 49. The solid bars represent the range of data which was used in the regression analysis and the slope is the same as generated by that analysis. The lines drawn over the bars represent the data correlation which would be required under the assumption that the slope is proportional to inverse base efficiency. As can be observed, the only data which require modification from the computer generated slopes are the two sets for which large scatter was present in the data, and it is problematic as to which curve fit actually represents the true behavior. Typical data scatter is indicated on the J79 curve.

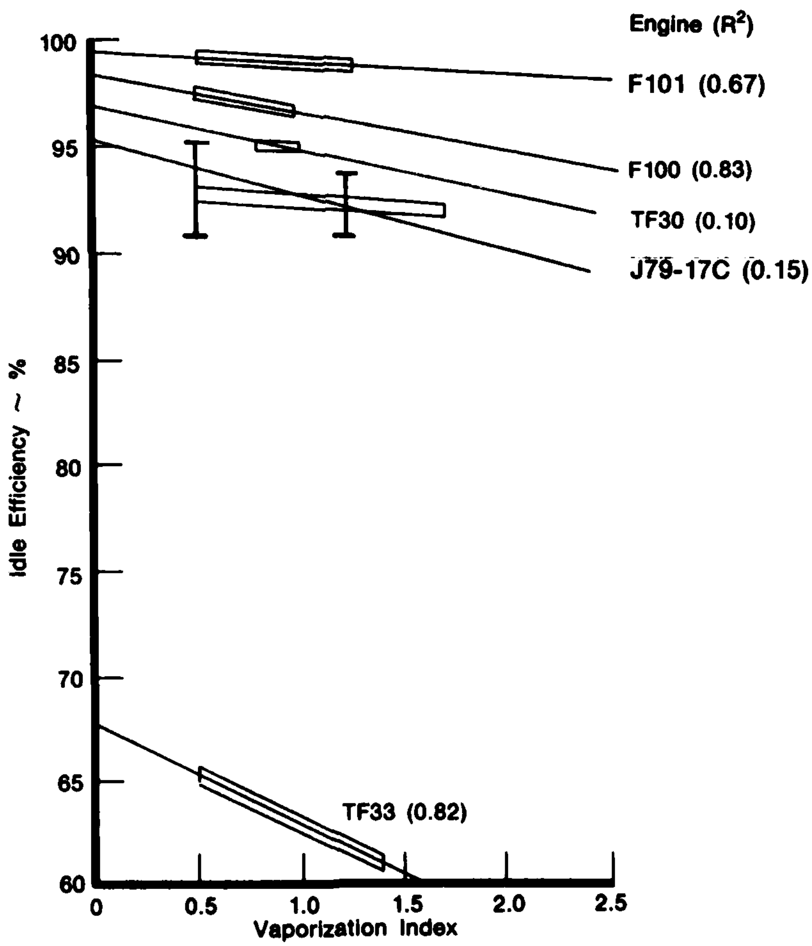


Figure 49. Idle Combustion Efficiency vs Vaporization Index

To correlate the sensitivity of idle efficiency versus vaporization index as a function of the engine parameters, an equation for idle efficiency is introduced. This equation, developed in reference (15), is:

$$Q' = \log\log\left(\frac{100}{\eta_c}\right) = (1.42 + \phi)\log\ 0.068\phi\left[\frac{W_a}{VP^{2\phi}}\right]\cdot\left(10^{-3.05\phi - 1.205}\, T_3^{1.23\phi - 1.205}\right)$$

$$+ (2 - 2.50\phi) \tag{26}$$

Where:	Q'	= Combustion efficiency correlation parameter	
	η_c	= idle combustion efficiency	%
	ϕ	= primary zone equivalence ratio	
	W_a	= primary zone airflow	kg/s
	V	= primary zone volume	m^3
	P	= combustor pressure	kPa
	T_3	= inlet temperature.	K

The results of this equation plotted against the derived slopes of efficiency versus vaporization index are shown in Figure 50. An excellent correlation is observed for these data. The correlation as presented here may be used to evaluate the effects of fuel properties variations on idle combustion efficiency as follows:

1. For a given engine with known efficiency on a baseline fuel, calculate the base value of the vaporization index (VI):

$$VI = \frac{\rho_f(SMD/SMD_{ref})^2}{\ln(1+B)} \tag{27}$$

2. Calculate the correlation parameter from:

$$Q' = \log\log\left(\frac{100}{\eta_c}\right) \tag{28}$$

3. From Figure 50 read the value of $\Delta\,\eta_c/\Delta$ VI corresponding to Q′

4. Calculate the value of the vaporization index for the new fuel properties

5. Calculate a new value of combustion efficiency at idle from:

$$\eta_c\,\text{new} = \eta_c\,\text{base} + \frac{\Delta\eta_c}{\Delta VI}(VI_{base} - VI_{new}) \tag{29}$$

In addition to this procedure, the correlation may be used to evaluate the impact of design changes on the sensitivity to fuel properties. To evaluate this effect the following procedure is used:

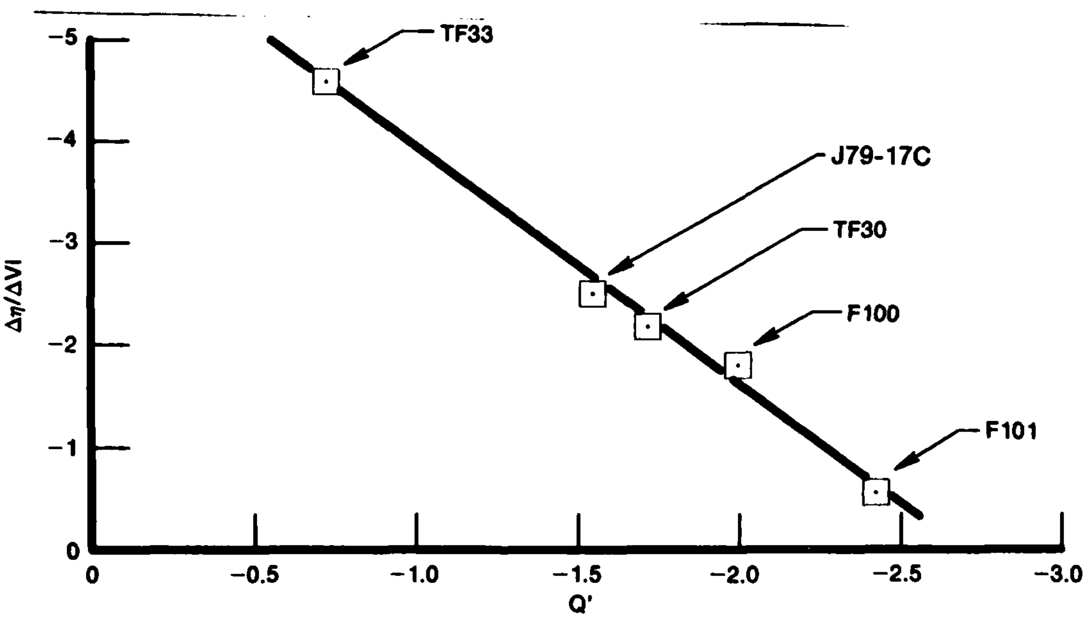
1. For a baseline and revised combustor design with known baseline idle efficiency, calculate Q'_{base} and Q'_{new}

2. Calculate the factor:

$$\frac{Q'_{new}}{Q'_{base}} \cdot \text{loglog} \left(\frac{100}{\eta_{c\ base}} \right) \tag{30}$$

3. Read the sensitivity correlation curve at this factor value to obtain the new design sensitivity to fuel properties. The curve should also be read at log log $(100/\eta c)$ to obtain the baseline sensitivity.

This procedure may be readily accomplished in either manual calculation or computer modes.



where:

$$Q' = (1.42 + \phi) \log \left\{ 0.068\phi \left[\frac{W_a}{VP^{2\phi}} \right] \cdot (10^{-3.05\phi - 1.205} T_3{}^{1.23\phi - 1.205}) \right\} + (2 - 2.5\phi)$$

Figure 50. Idle Combustion Efficiency Sensitivity vs Engine Correlation Parameter

C. GROUNDSTARTING CORRELATIONS

The process of groundstarting is controlled primarily by the formation of a vapor-phase fuel-air ratio within certain limits at relatively cold inlet temperatures. The correlating parameter for fuel properties which was selected is the vaporization index (VI) based on the 10% recovery temperature. This parameter, as shown in Section III-B, yielded statistically significant correlations for the F100, TF33, TF30, F101, J79-17C and TF41 engines.

Data from these combustors were correlated against differences in combustor design and operating variables through an analysis of the conditions which exist in the region of the ignition source or primary zone. The procedure which was employed was to utilize the computer-generated correlation curves from each engine test to calculate a value of the groundstart fuel-air ratio at a uniform level of the vaporization index and then correlate these values against combustor operating parameters. This approach minimizes the influence of experimental uncertainty associated with individual fuel tests on any given combustors.

The fuel properties correlations were presented in Section II. The general form of the regression equation is:

$$x = xo + x_1 \cdot VI, \tag{31}$$

Where:

x	=	minimum fuel flow rate or minimum fuel-air ratio
x_o	=	constant
x_i	=	slope
VI	=	vaporization index based on 10% recovery temperature of fuel.

Data are available at several airflows for the F100, TF30 and TF33 engines and several inlet temperatures for the F101, J79-17C and TF30 engines. The data regressions were either on fuel-air ratio or minimum fuel flowrate. Those which used fuel flow were converted to fuel-air ratio.

The selected correlation parameter for engine differences is U/PT, where:

U_a	=	air velocity at igniter, m/s
P	=	pressure, MPa
T	=	inlet temperature, K.

The velocity at the igniter is evaluated by using the combustor cross-sectional area at the igniter location and the total air flow through the combustor at that point. Using this parameter, all the test data were in the range of 0.03 to 0.29 m/MPa-K-s.

The fuel-air ratio, which was calculated at VI = 0.5 from the correlations, was corrected to the value at the igniter by using the percentage of total airflow at that location. This is referred to as the primary zone fuel-air ratio. Thus:

$$\left(\frac{f}{a}\right)_{\psi} = \left(\frac{W_f}{W_a}\right)\left(\frac{100}{\%\,W_a \text{ in primary}}\right) \tag{32}$$

The results of this analysis are shown in Figure 51 for two values of the vaporization index, i.e., VI = 0.5 and 1.0. The TF41 data are not shown due to a lack of definition of the airflow splits. A definite trend of primary zone fuel-air ratio with the correlation parameter is derived. At low values of the parameter, large fuel flowrates are required and as the parameter increases the required fuel-air ratio decreases. The trend is consistent for all five combustors evaluated and is statistically significant.

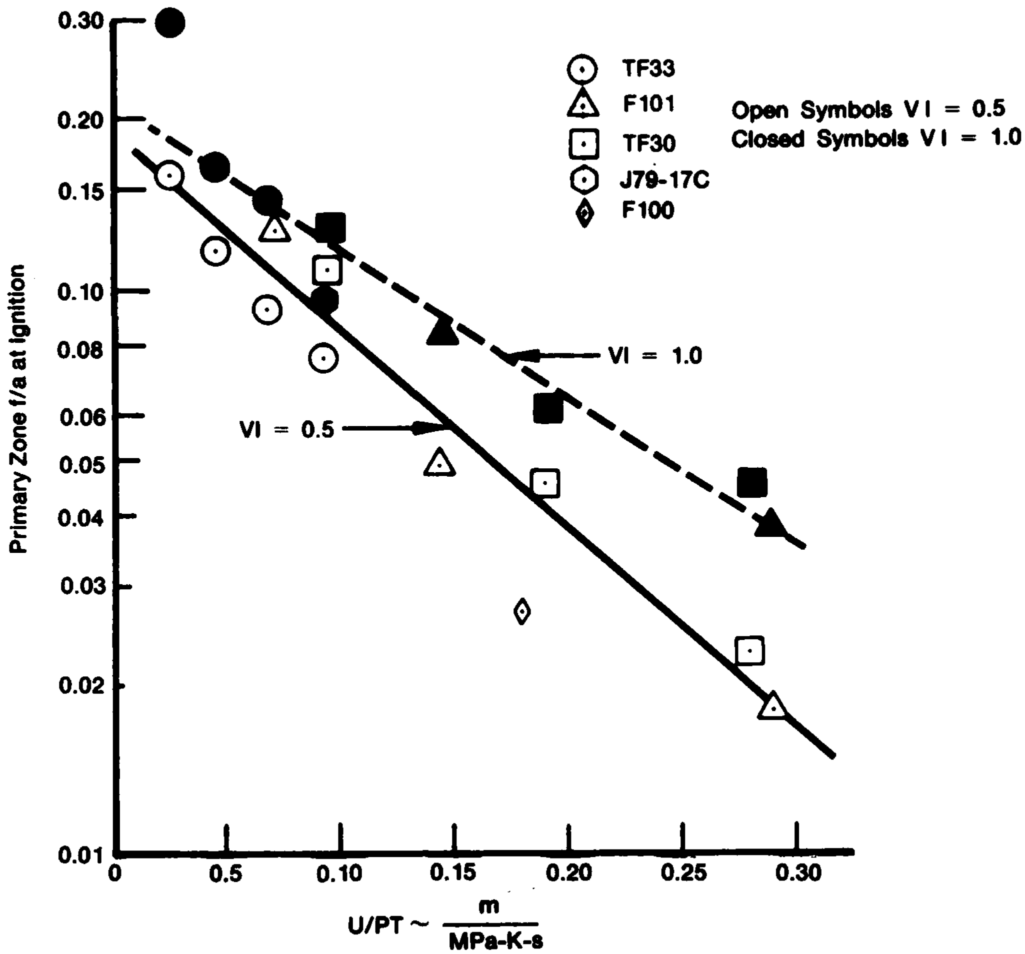


Figure 51. Groundstart Correlation at Two Values of Vaporization Index

To determine the influence of the vaporization index (VI) on the minimum groundstart fuel-air ratio, the difference between the values predicted for different levels of VI were correlated against the operation parameter, U/PT. The results are shown in Figure 52, where the ratio of the primary zone fuel-air ratios at VI = 1.0 and VI = 0.5 are plotted against U/PT.

A correlation is shown where this ratio is initially quite large and decreases as the parameter increases. Beyond a level of about 0.10, the ratio again increases. Although data are not available beyond about 0.30, it is anticipated that the ratio will ultimately decrease or become asymptotic.

The low values of U/PT, i.e., below 0.10, show significant scatter in the fuel properties effect. Extension of the correlation lines on Figure 51 indicate a decrease in the fuel sensitivity below a 0.10 while the specific data points show a strong upward trend. The most likely effect is strong dependence on fuel propeties at these difficult operating conditions.

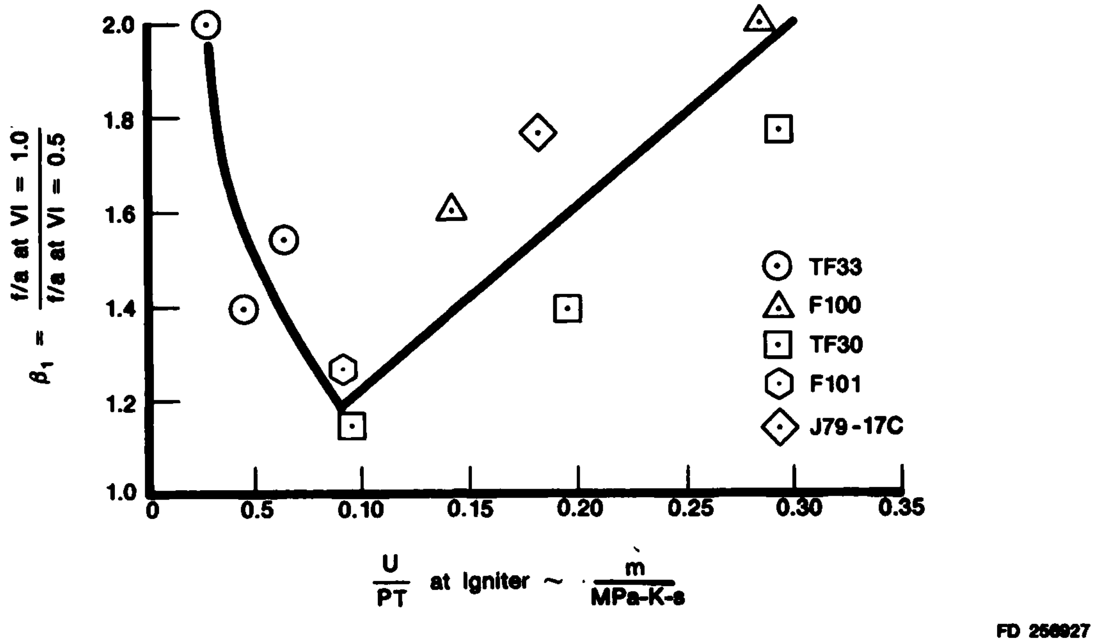


Figure 52. Sensitivity of Groundstart Fuel-Air Ratio to Vaporization Index

The results of this analysis may be utilized to evaluate the fuels effects as follows:

- For a given engine design and groundstart conditions, calculate U/PT as previously described.
- At this value of U/PT, from Figure 51 read the value of f/a for VI = 0.5 and the sensitivity factor, β_1 from Figure 52.
- For the given fuel, calculate the value of vaporization index based on the 10% recovery temperature.
- Calculate the value of the primary zone f/a with this fuel from:

$$f/a_{pri} = f/a_{(VI=.5)} \left(1 + (\beta_1 - 1) \cdot \frac{VI - .5}{.5}\right) \qquad (33)$$

This procedure may also be used when the groundstart capabilities on a given fuel are known. The procedure is as follows:

- Calculate the known fuel and engine values of U/PT and VI_{base},
- Calculate the VI of the new fuel,
- Read Figure 52 at U/PT to obtain β_1,
- Calculate the new fuel groundstart fuel-air ratio.

D. COMBUSTOR PATTERN FACTOR ANALYSIS

Combustor pattern factor is defined as:

$$P.F. = \frac{T_{4_{max}} - T_{4_{avg}}}{T_{4_{avg}} - T_3} \quad (34)$$

where:

T_4 = Combustor exit temperature, K
T_3 = Combustor inlet temperature, K

This index was previously correlated against fuel properties by use of the vaporization index (VI) based on the fuel 90% recovery or distillation temperature. This index was selected after analysis of several fuel properties' parameters. It is felt that this parameter correlates best with pattern factor since the larger amount of time required to vaporize the less volatile fuels reduces the time available for mixing to uniform exit temperature.

A summary of the VI correlations for six combustors is shown in Figure 53. These curves represent the mean data line which was obtained from the statistical regression analysis of the reported engine data as previously shown in Section III. The pattern factor data for most engines exhibited a large degree of scatter, which is evidenced in Figure 53 by the apparent behavior of the J79-17C and TF41 engines. The deviation in the trends is probably partially the result of the difficulty of these tests.

The prediction of pattern factor in a combustor requires evaluation of the quantitative effects of fuel nozzle and swirler design, primary zone aerodynamics, and dilution jet behavior among other parameters. As would be expected from this degree of complexity, there is little agreement as to a design system approach to pattern factor evaluation in engine design. An attempt to relate fuel properties to pattern factor changes through one design system or another would introduce the additional uncertainties associated with the system itself.

To avoid this problem, an approach was taken which relates the effect of fuel properties on pattern factor to the level of pattern factor of a base fuel. This trend is essentially one where the controlling processes are represented by the base fuels correlation and as that fuel parameter trends towards less efficient combustion, the pattern factor increases. This approach eliminates the problems inherent in the design system.

A correlation of the sensitivity of pattern factor to the vaporization index (VI) versus the base pattern factor in JP-4 fuel is shown in Figure 54. The data for the J79-17C and TF41 were deleted from this correlation. A definite trend of increased fuel sensitivity as pattern factor increases is demonstrated.

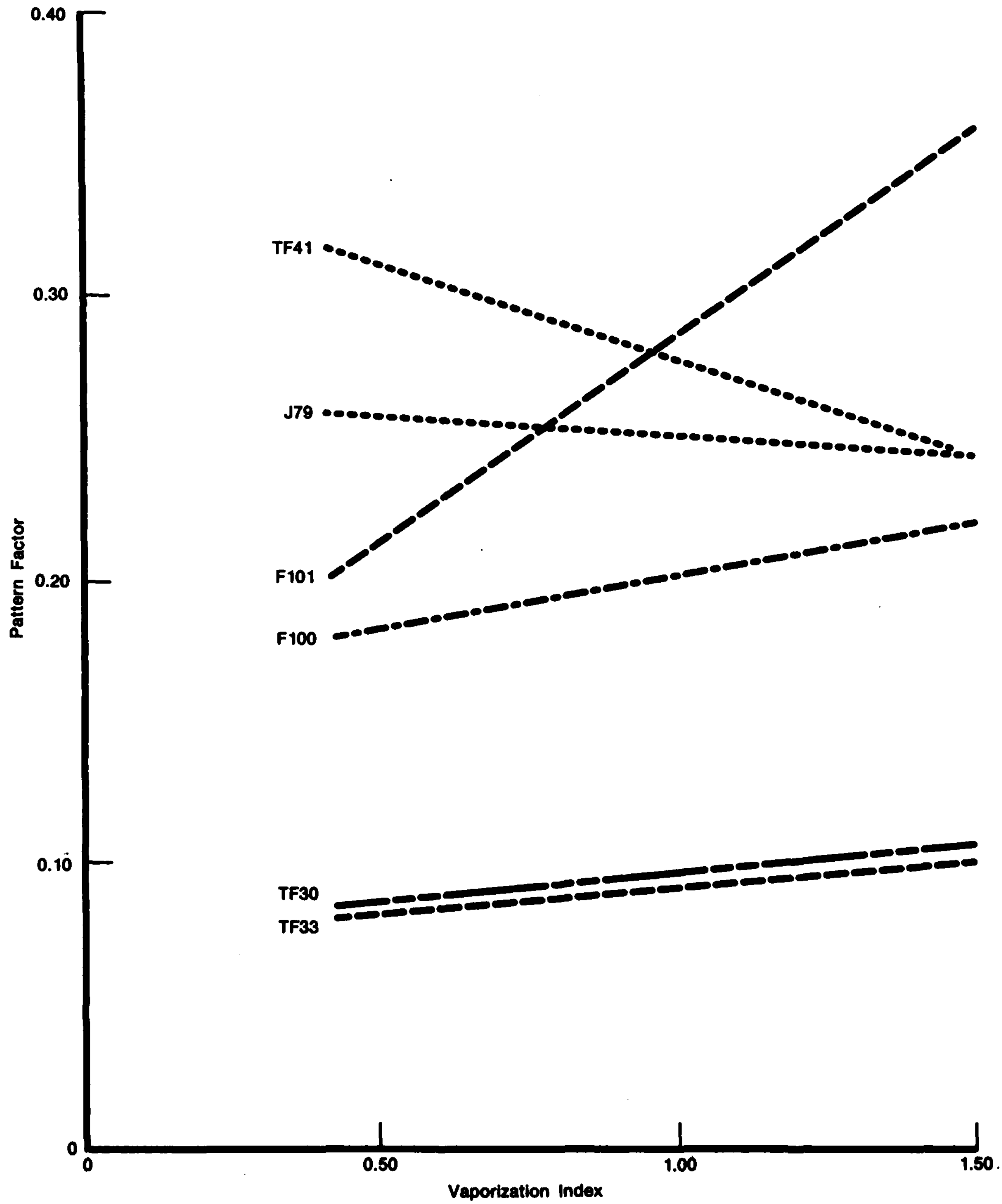


Figure 53. Pattern Factor Correlations vs Vaporization Index

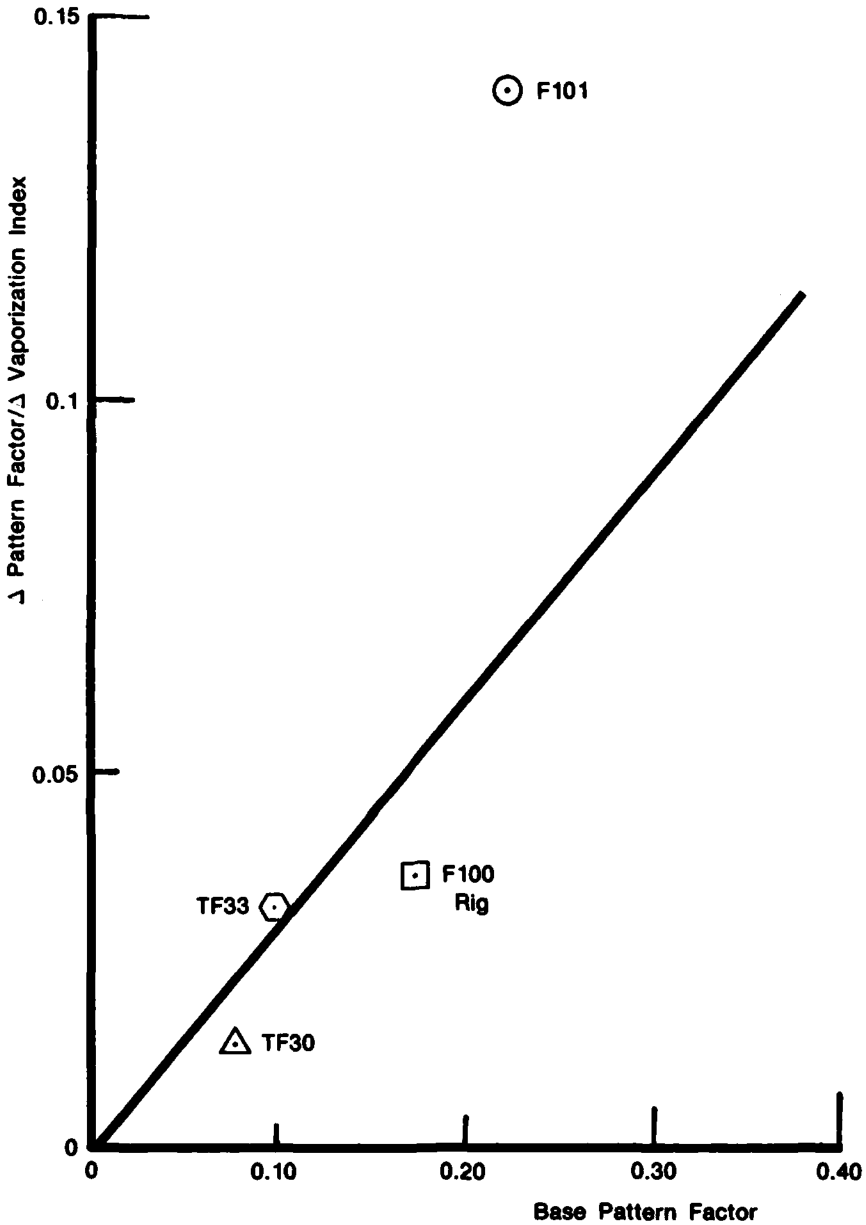


Figure 54. Pattern Factor Sensitivity vs Base Pattern Factor

The recommended procedure for evaluation of the sensitivity of the pattern factor for a given combustor to changes in the hydrogen content of the fuel is as follows:

- For a combustor whose pattern factor is known on the base fuel, read the curve from Figure 54 to obtain the sensitivity.

- For a design with unknown base pattern factor, it is necessary to first estimate the base value using a design methodology acceptable to the user. This estimate may then be used to enter Figure 54 and obtain the sensitivity factor.

- For either case, the projected pattern factor on the new fuel is calculated from:

$$PF_{new} = PF_{base} + (\Delta PF_{base}/\Delta VI)(VI - VI_{base}) \tag{35}$$

This value yields a representative response of pattern factor to fuel properties variations.

E. SMOKE EMISSIONS

The correlation of exhaust smoke number proceeded in a manner similar to the pattern factor results. The fuel property which was selected as most representative of the combustor response is the total hydrogen content of the fuel. The results of the regression analysis of the data are shown in Figure 55. The lines are the mean value relationships from the regressions.

A trend may be observed here which follows the same behavior as previously noted, where an increase in the smoke number on the base fuel is accompanied by an increase in the sensitivity of the smoke level to changes in the fuel hydrogen content. This effect may be used to develop a response relationship for prediction of smoke level on proposed alternative fuels.

As with pattern factor, this approach was selected due to the current uncertainties associated with any specific quantitative model for general smoke emissions. The response analysis is shown in Figure 56. This curve is used in a manner similar to pattern factor to evaluate the smoke level of a proposed new fuel.

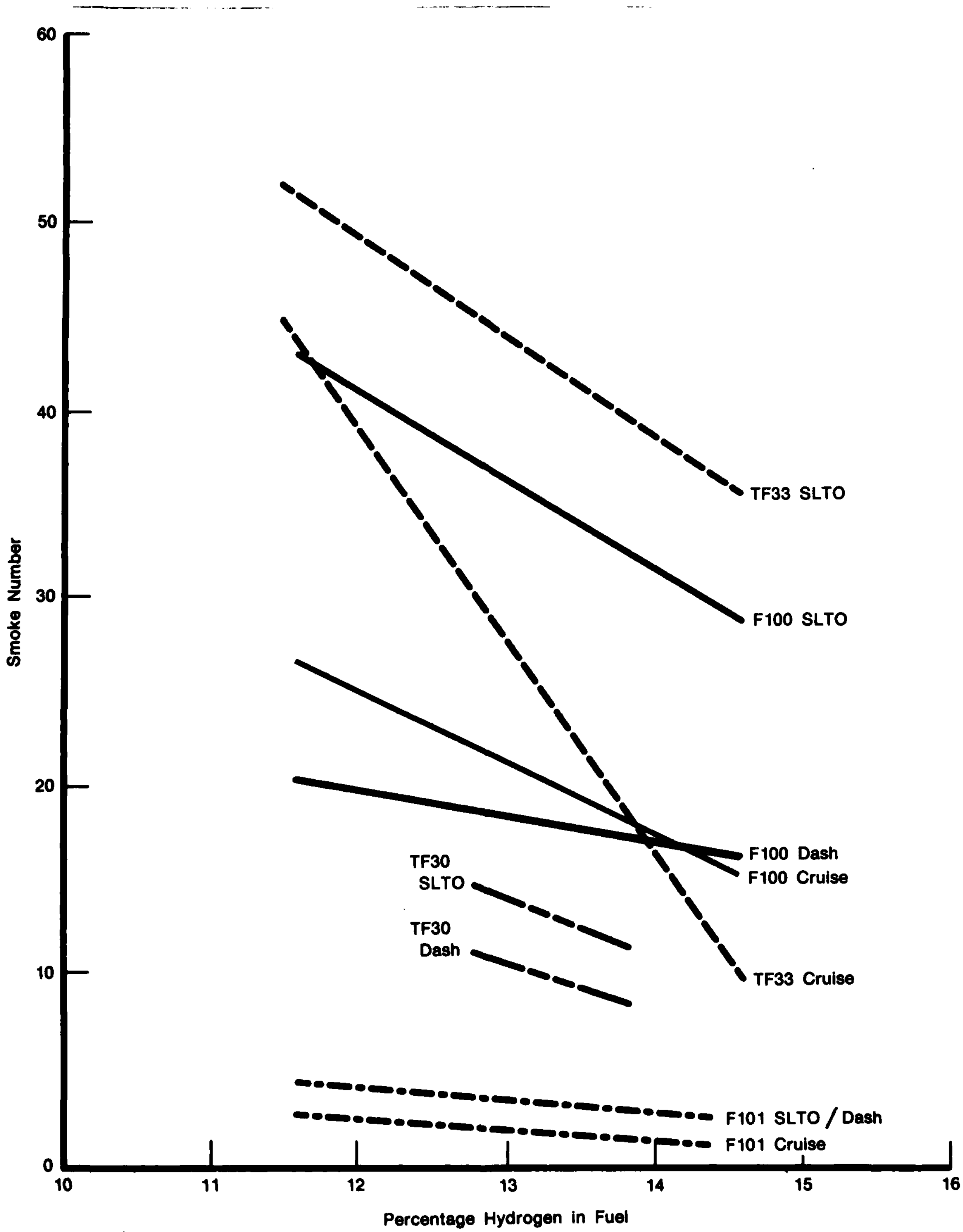


Figure 55. Smoke Number vs Hydrogen Content Correlation Results

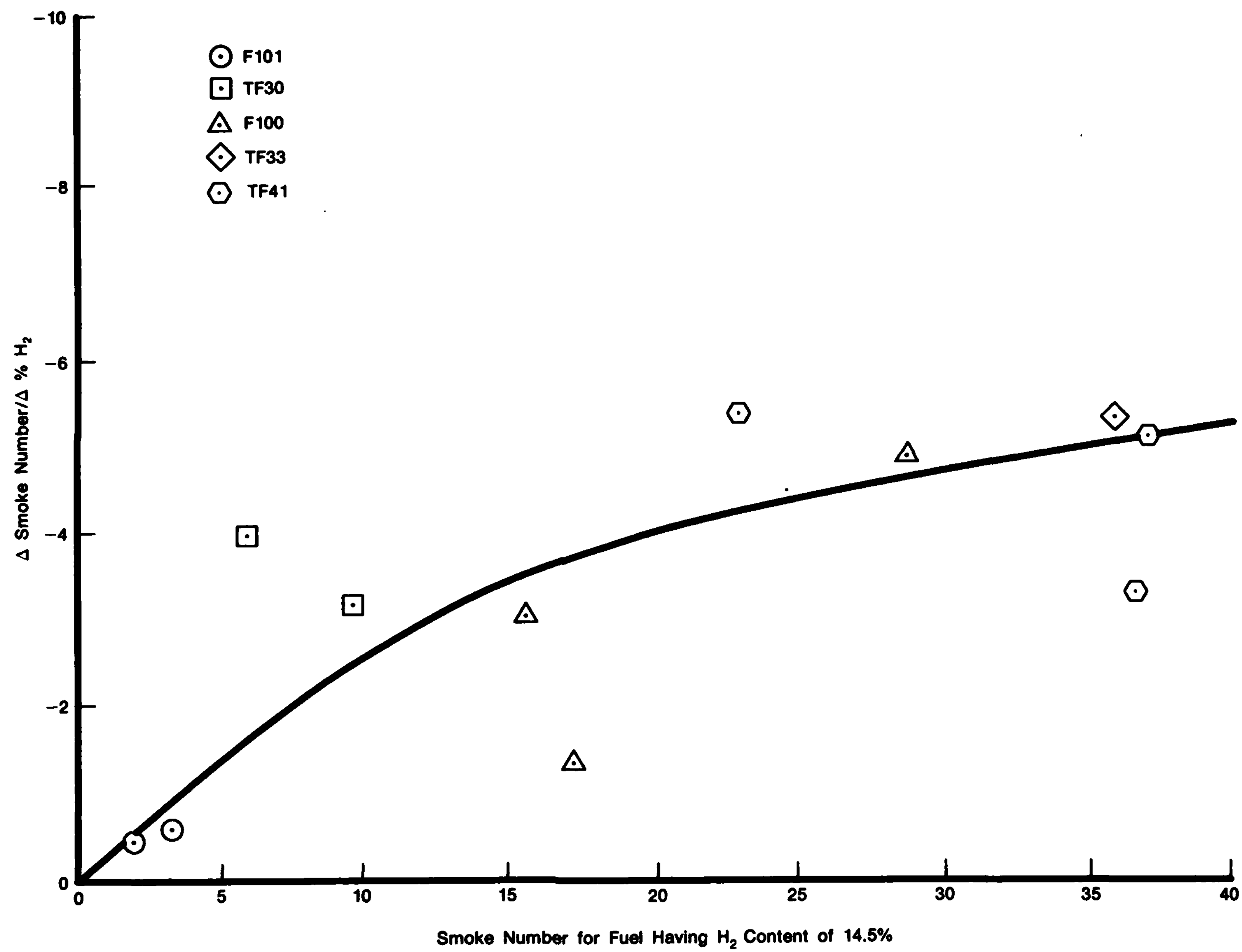


Figure 56. Smoke Number Fuel Sensitivity vs Base Value of Smoke Number

F. COMBUSTOR LINER METAL TEMPERATURES

The effect of the fuel properties on the combustor liner temperature was correlated through the use of a Liner Severity Parameter (LSP) which was defined as:

$$LSP = \frac{T_{L(max)} - T_3}{T_4 - T_3} \tag{36}$$

where:

T_3 = combustor inlet temperature
T_4 = average combustor exit temperature.

This parameter was correlated against the total hydrogen content of the fuel. A typical correlation set over various engines is shown in Figure 57 at sea level takeoff (SLTO) conditions. The degree of correlation is, in general, quite good.

The use of hydrogen content as the major fuel property is not surprising. An increase in smoke is directly related to an increase in the radiation level to the liner walls. The degree of correlation shown in Figure 57 is good, considering the differences in the cooling methods and effectiveness of the various engines.

Correlation across the various engine designs was done in the same manner as for pattern factor and smoke number. A quantitative analysis which predicts the maximum metal temperature of all combustor liner designs would require detailed data beyond the level of that reported. Also, the quantitative prediction for proposed designs would be subject to similar constraints.

The selected correlation approach relates the degree of fuel sensitivity to the initial value of liner severity parameter on the base fuel. This correlation result is shown in Figure 58. This correlation is used in the same manner as previously discussed for pattern factor and smoke.

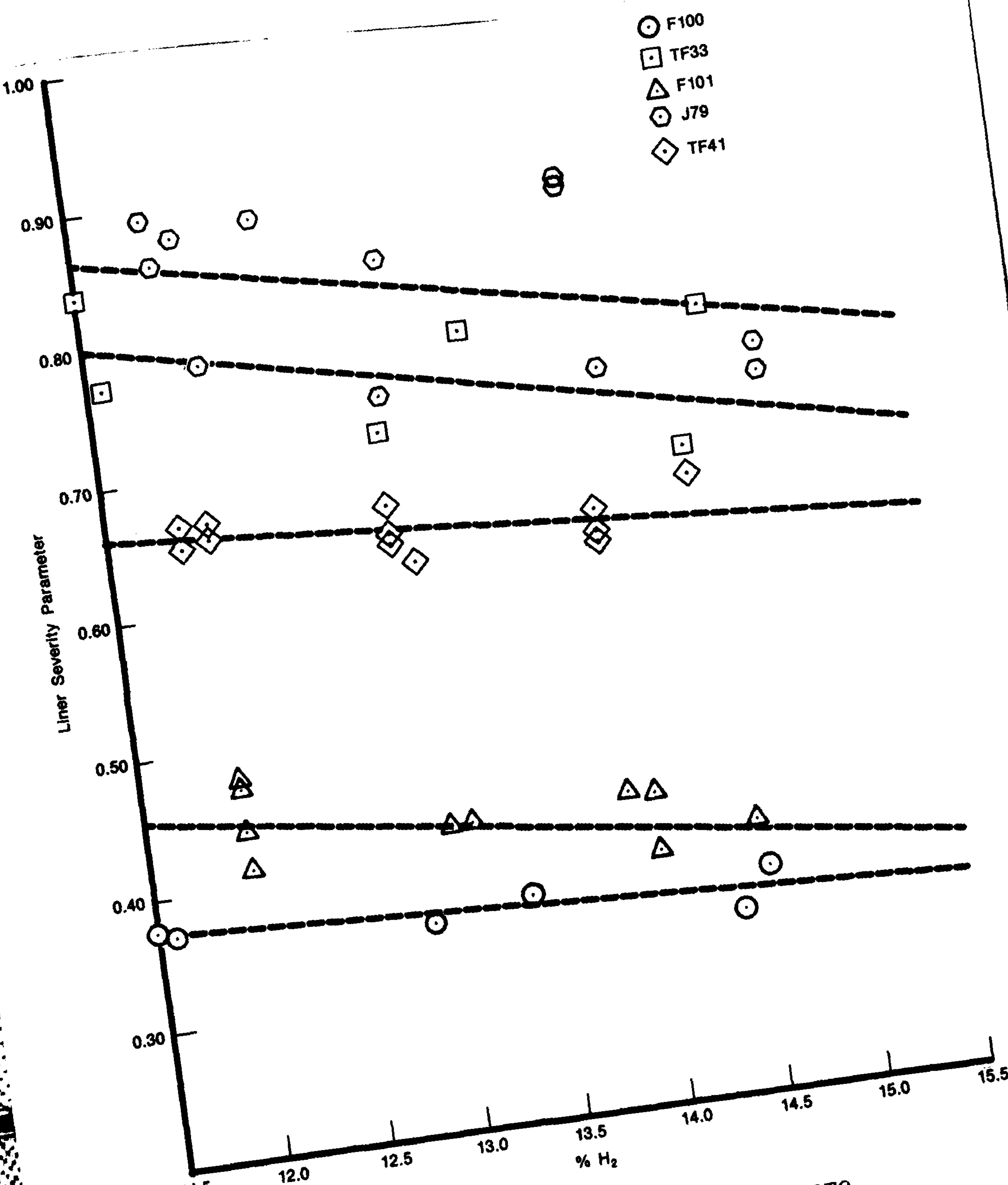


Figure 57. Liner Severity Parameter vs Hydrogen Percentage at SLTO

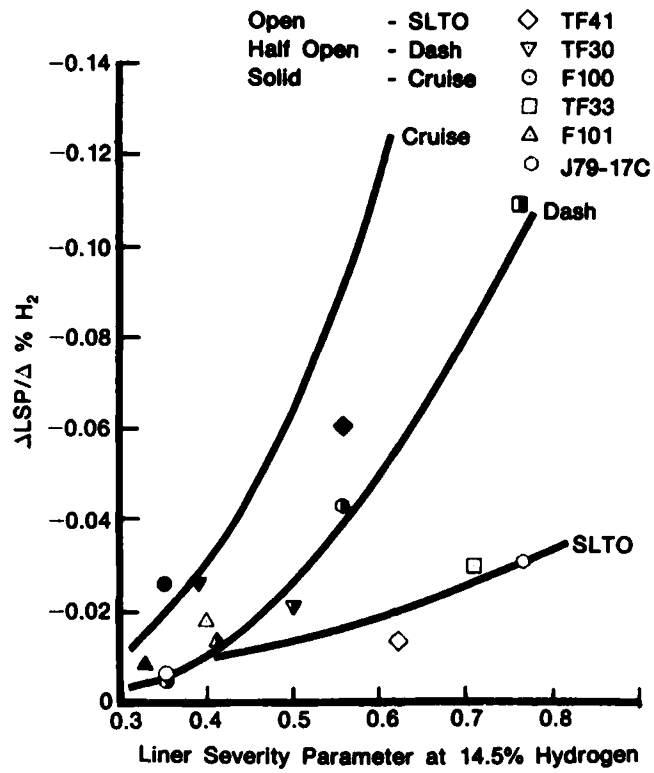


Figure 58. Liner Severity Parameter at 14.5% Hydrogen

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Based upon the results of the analyses conducted under this program, a number of conclusions have been drawn relative to the effect of fuel property variations on combustor performance and on the relationship of these trends to combustor design variables.

1. At the conditions of interest for most of the engines studied, ignition, combustion efficiency and pattern factor variations are controlled by fuel atomization and vaporization. Correlations which relate vaporization rate to ignition, combustion efficiency and pattern factor with good statistical significance were developed.

2. The effect of fuel properties on altitude ignition are quite different for pressure-atomizing and air-atomizing nozzles. For the fuels evaluated, increased droplet size and reduced volatility show a greater effect on altitude relight with pressure atomizing nozzles.

3. A convenient technique for varying fuel properties to determine effects governed by atomization and vaporization on combustor operation and performance is to vary fuel inlet temperature.

4. Smoke and combustion liner radiative heating correlate well with fuel hydrogen content. Incorporation of fuel droplet size or multicyclic aromatic concentration in the correlation did not statistically improve the correlation.

5. The sensitivity of a particular combustor to fuel property changes is generally proportional to the level of the performance parameter in question with some reference fuel. For example, the higher the combustor smoke number found with JP-4, the more sensitive the combustor is to increased smoke level with lower hydrogen content fuels. This observation is perhaps the most important conclusion of the entire study and leads to two additional conclusions:

    a. The observed performance with a reference fuel provides a convenient basis for correlation of fuel effects, and

    b. A well designed combustor with high combustion efficiency, low pattern factor, low smoke point, etc., will generally provide far better accommodation of broad specification or alternative fuels than more marginal combustors.

The fuel correlations developed under this program provide good insight into the extent to which fuel properties affect the performance and operation of aircraft gas turbine engines. The predicted trends may be used to assess the impact of fuel property variations on gas turbine combustor operation. On the other hand, in some cases, significant scatter in the correlated data was found, indicating either possible inaccuracies in the test data or of second order effects that could not be determined. It should be pointed out that the data upon which the correlations have been based is combustor rig data. The use of rig data to predict engine performance has always presented uncertainties. The following recommendations are suggested as a means of improving the accuracy and applicability of the correlations.

1. Before the correlations presented in this report can be used to predict engine performance, they should be anchored to baseline engine data and the correlation trends reconfirmed. Because of the critical effect of pattern factor on turbine life and the difficulties in obtaining valid pattern factor data from rig tests, instrumented engine data to obtain fuel related pattern factor changes are essential.

2. While the available test data are generally of a high quality, further improvements in data accuracy are required if second order effects are to be determined. Improved data will require improved instrumentation, more complete instrumentation and testing at conditions which are more closely representative of full scale engine operation.

3. It should be recognized that the accuracy of the fuel correlations is enhanced by using a broad range of the key properties which affect the correlations. The fuels tested under the Reference 1 through 5 evaluations cover all of the fuel property variations likely to be encountered in the forseeable future; however, use of an even wider range of fuel properties and composition would help in achievement of better correlations by producing fuel effects which are larger relative to test inaccuracies.

4. In selecting fuels for future fuel effect testing, priority should be given to those fuel properties which have been found to most significantly affect combustor operation. Hydrogen content and viscosity are of primary importance. Density and volatility are of secondary importance. And the potential second order effects of naphthalene concentration should not be ignored even though these effects have not been quantified under this study.

5. Where it is difficult to obtain a sufficiently broad range of fuel properties through preparation of petroleum blends, use of pure compounds and/or testing over a wide range of fuel combustor inlet temperatures should be considered.

6. It should be recognized that the combustor instrumentation is not the only source of data inaccuracy. In future tests, even greater care should be taken to fully and accurately characterize fuel properties and composition. Judicious fuel sampling and careful fuel handling should be conducted to assure that fuel contamination has not been encountered.

7. As additional test data (engine and rig) become available, the correlations presented here should be reexamined and updated as necessary.

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